Group Descriptions

The Physics Division Management Team. Front row (from left to right): Jack Shlachter, Mary Hockaday, Andrea Palounek, Susan Seestrom, Pam French, Stephanie Archuleta, and Jeff Schinkel. Back row: Kurt Schoenberg, John McClelland, Lynn Veeser, Martin Cooper, Juan Fernández, Bob Scarlett, and Carter Munson (not pictured: Doug Fulton).

P-21: Biophysics

W. Robert Scarlet,
Acting Group Leader

Introduction

The Biophysics Group (P-21) was founded in 1988 with the goal of applying the scientific and technical resources of Physics Division to the biosciences. Our mission is to contribute to an understanding of biological phenomena by means of the scientific, technical, and conceptual resources of physics; to use biological systems to elucidate general physical principles underlying complex phenomena; and to apply, where appropriate, our scientific and technical capabilities to core Laboratory programs.

Just as the 20th century is regarded as the century of the physical sciences, the 21st century will likely become the century of the biological sciences. P-21 and biophysics as a discipline are well-positioned to contribute to this biological revolution-in-progress through our emphasis on understanding biological systems using the scientific, technical, and conceptual resources of physics. Recent advances in biophysical measurement and in molecular biology are beginning to allow detailed physical understanding of biological phenomena that were previously understood only in qualitative terms.[1] P-21 is well placed by virtue of its capabilities and research interests to contribute significantly to this important trend in the biosciences.

In addition to the goal of achieving a physical understanding of biological phenomena, research in P-21 shares a number of other common characteristics. Specifically,

- we investigate the relationships between structure, dynamics, and function of biological phenomena over a wide range of scales (*e.g.*, from biomolecules to the whole human brain);
- we make extensive use of detection, imaging, and reconstruction techniques (*e.g.*, x-ray crystallography, single-molecule electrophoresis, high-speed photon-counting optical imaging, magnetic resonance imaging [MRI], and magnetic-field measurements using technologies based on superconducting quantum interference devices [SQUIDs] as shown in Figure 1);
- we attempt to achieve a detailed interplay between high-resolution physical measurement and large-scale computational modeling and analysis of complex systems;
- we develop new facilities in support of our scientific and technical goals, including
  - a dedicated x-ray beam line for protein crystallography at the National Synchrotron Light Source at Brookhaven National Laboratory (Brookhaven);
  - a large-bore MRI facility;
  - a high-speed, time-domain measurements and electronics laboratory and fabrication facility; and
  - a growing SQUID applications laboratory at Los Alamos;
- we depend heavily on the tight connection and daily interplay between biologists and physical scientists within the group, the division, and the Laboratory; and
- we apply the knowledge, techniques, and capabilities developed in our biological studies to problems of national security and those of specific interest to the Laboratory when our ongoing efforts can offer unique solutions and significant mutual benefit.

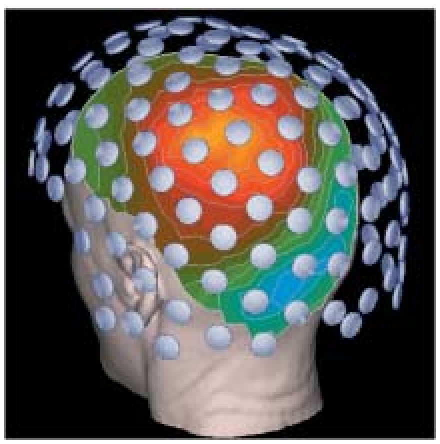


Figure 1. Our whole-head MEG system uses SQUID sensors to record the magnetic fields produced by active populations of neurons.

During the past two years, P-21 had a number of major accomplishments, including successful demonstration of both active and passive photon-counting imaging for a variety of applications, significant contributions to measurement and analysis of magnetic fields for functional human brain imaging, and award of a National Institutes of Health (NIH) Center Grant for a LANL-led research initiative in structural genomics. Our scientific and technical activity lies in six major areas, which are discussed individually below.

Protein Structure, Dynamics, and Function

P-21 researchers and collaborators in Bioscience (B) Division and elsewhere have been developing and promoting the field of structural genomics over the last four years. This year, the dream of a broad-based attack on protein structures has been made real through establishment of a NIH-funded Center for Structural Genomics based in Los Alamos. Associated with the Center is an international consortium, the Mycobacterium Tuberculosis Structural Genomics Consortium. This consortium consists of 60 laboratories from 30 institutions in 9 countries. It has the stated goal of solving and analyzing roughly 400 structures of proteins from the bacterium that causes the disease tuberculosis (TB). TB kills more adult humans in the world than any other pathogenic organism. The resulting database of linked structural and functional information is expected to form a lasting basis for understanding pathogenesis by TB bacteria and should pinpoint new targets for drug action against the disease.

To accomplish this, we are developing scalable technologies that will make structural genomics feasible. Further, we will demonstrate an approach to structural genomics that allows researchers around the world to collaborate on a defined set of structural targets. Consortium laboratories have collectively thus far been responsible for 3.3% of all protein structures in the Protein Data Bank and have extensive records of methods development for high-throughput structure determination and analysis. The consortium will have centralized facilities that will carry out an increasing fraction of routine tasks such as protein production, crystallization, and x-ray data collection. P-21 researchers are responsible for overseeing the primary x-ray data-collection facility (beamline X8-C at Brookhaven). In addition, we are developing new methods and instrumentation for improved data collection and analysis.

Functional Brain Imaging

A recent unpublished NIH position paper states "Brain imaging is one of the most rapidly advancing fields in science today." More than any other area of biology, it is a field in which the progress of research is dependent on improving technologies and computational power.

> *"...[R]apid improvements in brain-imaging methods provide our best hope for understanding brain mechanisms that play a role in mental illness and, eventually, for improving our ability to diagnose, treat, and prevent neurologically based brain disorders."*

P-21's effort in functional brain imaging focuses on the combined use of magnetoencephalography (MEG), anatomical MRI, functional MRI (fMRI), and optical-imaging techniques to develop improved techniques for noninvasive imaging of the human brain. High-resolution MEG arrays and optical-imaging techniques are also used to image neural activity directly from the brains of experimental animals (see Figure 2). Together with collaborators at the University of New Mexico School of Medicine, Albuquerque Regional Federal Medical Center in New Mexico, Massachusetts General Hospital in Boston, and the University of Minnesota School of Medicine in Minneapolis, P-21's work in functional brain imaging contributed significantly to the recent formation of the $60M National Foundation for Functional Brain Imaging to be headquartered in Albuquerque.

Members of P-21 are engaged in projects to design improved multichannel magnetic sensors, develop more accurate mathematical models for localizing the electrical and magnetic signals from the brain, validate MEG using known current sources in computational and physical models of the brain, and use MEG to address important questions in basic neuroscience and in research on neurological and psychiatric disorders.

Combining MEG and anatomical MRI with other functional imaging techniques such as fMRI and positron emission tomography (PET) offers the opportunity of increasing the combined spatial and temporal resolution of functional imaging techniques well beyond that of any single method, as noted in the NIH quotation above. We are engaged in developing mathematical models for combining these alternative forms of brain imaging. This work is part of a nationwide effort to develop three-dimensional (3-D) computational models of the brain in which a variety of structural and functional information can be represented for storage, retrieval, and analysis.

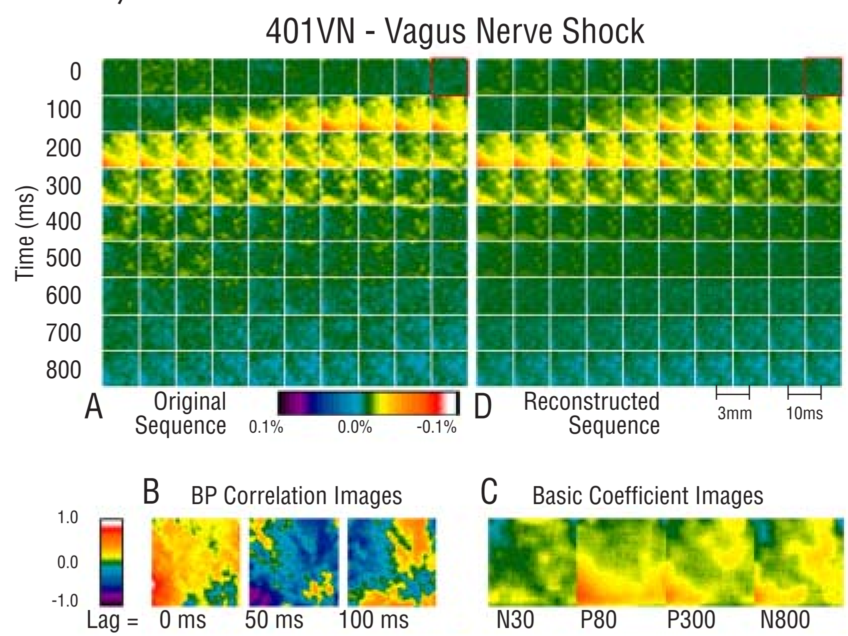


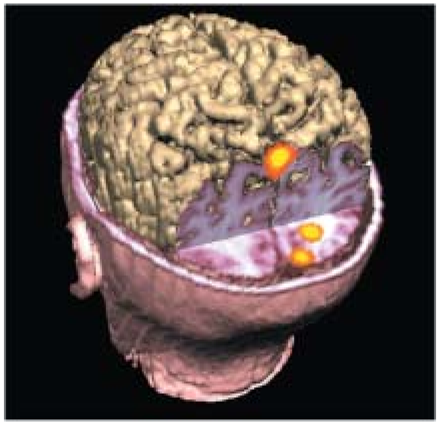
Figure 2. High-resolution optical-imaging techniques allow for images such as this, which accurately measure neural activity directly from the brain.

SQUID-Based Sensors and Applications

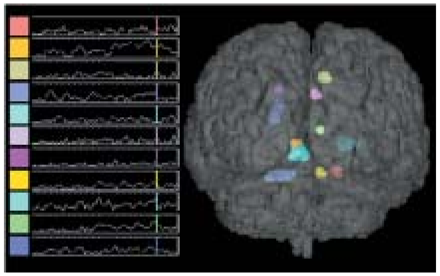
The goals of our MEG SQUID sensor projects are to develop, test, and evaluate sensor systems, numerical techniques, and computational models for functional imaging of the human brain using MEG. MEG involves the use of SQUIDs to measure magnetic fields associated with human brain activity. Measurement of the magnetic fields of the brain (which are approximately a billion times smaller than Earth's) requires sensitive magnetic sensors, magnetic shielding from the environment (currently implemented through a shielded room), and advanced signal-enhancement and modeling techniques. Because magnetic fields readily penetrate the skull, MEG offers the potential for noninvasive measurement of brain function in much the same way that computed tomography and MRI allow the noninvasive detection of brain structure. MEG has therefore generated considerable interest in its possible use as a tool in basic neuroscience for functional mapping of the human brain, as a clinical tool for the assessment of neurological and psychiatric disorders, as a possible source of signals for use in the development of neural prosthetics and human-machine interfaces, and in other applied contexts.

MEG directly measures a physical effect of neuronal currents with temporal resolution not limited by the sluggish vascular response, unlike PET and fMRI that measure hemodynamic changes associated with neuronal activity. High temporal resolution is particularly important for studying neurological disorders such as epilepsy, where temporal information is a major diagnostic, and for fundamental studies of synchronization and oscillatory brain activity. Our whole-head MEG system is based on the P-21 patented principle of superconducting image-surface gradiometry, where magnetic sources are imaged on the surface and magnetometers near the surface sense the combined fields as if the sensors were gradiometers (see Figure 3). Fabrication and assembly of this system are nearly complete. This system will play a major role in the National Foundation for Functional Brain Imaging.

Significant progress has also been made in development of novel, improved approaches to the MEG forward and inverse problems. In the case of the forward problem, the two major existing approaches are spherical (or spherical-shell) models and boundary-element models. Spherical models have the advantage of computational simplicity, but they can result in significant inaccuracies in regions of the head that depart from spherical geometry. In contrast, boundary-element models are more accurate but at a significant increase in computational complexity. Working with our collaborators, we have developed an alternative to the spherical and boundary-element approaches to the forward problem, termed the weighted multisphere approach because it uses multiple spheres fit to the local curvature of the skull.



(a)



(b)

Figure 3. In our whole-head MEG system (shown in Fig. 1), the locations and time courses of active neural populations are calculated using computer models (a) and displayed on MRI images of brain anatomy (b).

This approach can achieve accuracies approaching those of the boundary-element model with computation time comparable to that of the simple spherical model. With respect to the inverse problem, members of P-21 recently demonstrated a new probabilistic approach based on Bayesian inference. Unlike all other approaches to the inverse problem, this approach does not result in a single “best” solution to the problem. Rather, it estimates a probability distribution of solutions upon which all subsequent inferences are based. This distribution provides a means of identifying and estimating the features of current sources from surface measurements that are most probable among the multiple solutions and can account for any set of surface MEG measurements. The promise of this approach has been demonstrated using computer simulations and experimental data. In particular, we have demonstrated for the first time that information can be extracted not only about the locations of regions of activity but also their extent.

In addition to applications of SQUIDs to MEG and related biological applications, members of P-21 have made significant accomplishments in applying these same sensors to the nondestructive evaluation of nuclear weapons components and materials. As described in detail in a research highlight in Chapter 2 of this report “SQUID Array Microscope —An Ultrasensitive Tool for Nondestructive Evaluation,” a SQUID microscope has been designed, built, and tested for applications in the Enhanced Surveillance Program. This system uses a SQUID cooled by liquid nitrogen to map magnetic fields produced by eddy currents in a sample at room temperature. Material defects in the sample (due, for example, to cracks, seams, stress fractures, corrosion, or separation of layers) perturb eddy currents and produce magnetic-field anomalies when compared to uniform, defect-free materials. Such anomalies can be detected even if the material defects are located below the surface in deeper layers of the sample. This latter capability is particularly important for nondestructive evaluation of weapons components and materials.

In the first full year of the project, the SQUID microscope team designed, fabricated, and performed successful initial tests of a SQUID microscope based on high-critical-temperature SQUID sensors. This work won P-21’s SQUID Microscope Team a Los Alamos Distinguished Performance Award for 1998. Their success was based in part on their ability to exploit P-21’s extensive experience in applications of SQUID sensors for noninvasive measurement of human brain function. Given this successful proof of concept, the team is now refining the SQUID microscope design to improve its sensitivity and resolution, to permit operation in magnetically noisy environments, and to use higher-frequency induction fields.

Biologically Inspired Hardware, Computation, and Robotics

P-21 is making a significant effort in the study of adaptive and biologically inspired computation. Biological systems are capable of processing sensory information distributed across tens of thousands of input channels and are furthermore able to do so in real-time. Modern digital computers, however, are typically overwhelmed when confronted with similar massively parallel input streams. Unlike man-made sensors, which encode input signals as simple scalar magnitudes, biological neurons represent information as trains of uniform impulses. By transiently synchronizing their impulse activity, biological networks exploit this extra encoding dimension in order to separate signal from noise and to separate multiple signals in the input space from each other. We are beginning a study to make use of existing expertise, both at the Laboratory and among our university collaborators, to further explore and develop this promising new field of technology. A specific application is autonomous, visually guided navigation. We are approaching this area using modeling of visual neuronal processes and application of hardware neuromorphic chips developed by collaborators at the University of Delaware and by developing and testing algorithms used to autonomously guide a small wheeled vehicle. For more information on this research, see the research highlight "Synchronization of Spiking Neurons in a Computer Model of the Mammalian Retina" in Chapter 2.

Single Molecule Spectroscopy and Electrophoresis

P-21 and its collaborators have extended their work on the detection and characterization of single molecules in a liquid. The goal of this research is to measure and characterize the spectroscopic properties of individual molecules (see Figure 4). Such spectroscopic measurements can be used to identify the presence of a particular molecular species in an extremely dilute solution, or they can be used to probe the local environment that surrounds an individual molecule. The former capability promises a new level of speed and sensitivity for medical diagnostics, whereas the latter capability makes it possible to study properties of biological systems that cannot be measured when a lack of sensitivity confines measurements to the determination of the average properties of a large ensemble of microenvironments. Thus far, the spectroscopic properties measured at the single-molecule level include emission spectra, fluorescence lifetime, and total emission intensity. Recently the single-molecule spectroscopic approach has been extended to include single-molecule electrophoresis and approaches to ultrasensitive detection of viral and bacterial pathogens in soil and water samples. See the research highlight "Single-Molecule Detection of Specific Nucleic-Acid Sequence" in Chapter 2. We are exploring additional applications for basic research and for medical diagnostics.

Figure 4. The single-molecule electrophoretic analyzer detects single labeled molecules in solution.

High-Speed Electronics Team

Already a diverse group, P-21 became more diverse and significantly stronger with the addition in December 1997 of the electronics team formerly in the Hydrodynamics and X-Ray Physics Group (P-22). Previously a key element of the nuclear test program at the Nevada Test Site, the electronics team refocused its efforts to other defense and civilian needs with the cessation of nuclear testing. We now, quite literally, have the capability within P-21 to take an idea from the "gleam-in-the-eye" stage, through basic and applied research, to a fully developed, fieldable instrument for direct use by sponsors or industrial partners. The electronics team brings substantial capabilities in electronics design, fabrication, and implementation to P-21 that are of great value in their own right and have significant potential for the enhancement of our biological programs. In less than one year, the electronics team has made contributions in all of the focus areas listed above, including exploration of detectors derived from remote ultra-low light imaging (RULLI) techniques for applications in biomedical imaging and single molecule detection, contributions to high-throughput protein purification for the structural genome project, and other areas.

Currently the major effort of the high-speed electronics team is development and application of ultra low-light imaging through the RULLI project. They have demonstrated the capability to build remote images from a variety of platforms using only the ambient illumination provided by starlight. The team has also demonstrated active imaging of objects using a laser illuminator and precise timing to produce a three-dimensional literal image cube. The team is working to both improve and extend the technology as well as to apply it to various problems including imaging of optical signals rising from nerve activity, understanding the propagation of light in clouds, and national-security applications.

Further Information

For further information on P-21's projects, refer to the project descriptions in Appendix A of this progress report. Some of our major achievements are also covered as research highlights in Chapter 2, as mentioned above. These include SQUID microscope development, single-molecule detection, neuronal synchronization research, and the development of the virtual pinhole confocal microscope.

References

[1] D. A. Doyle, J. M. Cabral, R. A. Pfuetzner, *et al.*, "The Structure of the Potassium Channel: Molecular Basis of K^+ Conduction and Selectivity," *Science* 280, 69 (1998).

P-22: Hydrodynamics and X-Ray Physics

Jack S. Shlachter, Group Leader
Lynn R. Veeser, Deputy Group Leader

Introduction

The mission of the Hydrodynamics and X-Ray Physics Group (P-22) is to solve challenging experimental-physics problems relevant to our national security—aiming to reduce the threat of war by helping to ensure the reliability of our nuclear-weapons stockpile and by limiting the proliferation of weapons of mass destruction. Our experiments focus on the hydrodynamic properties of materials as they undergo explosive and implosive forces. For nuclear weapons and other highly dynamic systems, knowledge of material behavior under extreme physical conditions is important for developing computational models. Our x-ray capability is predominantly involved in the diagnosis of dynamic material behavior.

To fulfill its mission, P-22 develops and maintains a creative multidisciplinary team, broad physics and engineering capabilities, and state-of-the-art technologies. Experimental efforts in P-22 cover a wide range of physics disciplines, including hydrodynamics, x-ray spectroscopy and imaging, plasma physics, radiation hydrodynamics, optics and fiber optics, microwaves, electromagnetics, atmospheric physics, and atomic physics. In support of these experiments, P-22 has expertise in a variety of engineering disciplines, including analog and digital electronics; electro-optics instrument design and fabrication; high-voltage, low-inductance pulsed-power engineering; and fast-transient data recording. P-22 is also the operations group for the Atlas High-Energy Pulsed-Power Facility. This high-energy experimental facility will provide a valuable laboratory test bed for the investigation of dynamic material properties.

The mainstay of P-22 has traditionally been its support of the nuclear-weapons program. P-22 continues this tradition by supporting science-based stockpile stewardship (SBSS), which is the foundation of the present Los Alamos nuclear-weapons program. SBSS requires the development of complex experiments on diverse facilities to address the relevant physics issues of the enduring stockpile. In P-22, we support SBSS by applying the scientific and engineering expertise that we developed for the nuclear test program to investigate and understand primary and secondary weapons-physics issues that are crucial in a world without nuclear testing.

Figure 1. P-22 data-recording trailer at the Nevada Test Site (NTS) U1A underground test facility. The trailer uses modern fiber-optic systems and state-of-the-art digitizers and timing systems to gather and record data from explosive experiments located almost 1,000 ft below ground.

Nevada Test Site

P-22 is deeply involved in protecting and archiving the volatile test data it took during more than three decades of underground nuclear testing at the Nevada Test Site (NTS). Our goal is to bring the group's data to a stable and readily accessible state. These data will be used to benchmark all future calculational tools. The archiving activities constitute a significant effort in P-22 and involve individuals responsible for the original execution of underground nuclear tests as well as trainees. Many of the numerical algorithms developed for analyzing the information from underground tests have been ported to modern computer platforms as part of our effort to preserve these valuable and unique data.

In addition, P-22 continues to participate in experiments performed underground at NTS—both to study the physics of weapons performance and materials and to maintain our readiness to support a resumption of nuclear testing should the need arise. These experiments increase our understanding of weapons science by allowing improvements in code calculations and in estimates of the severity of problems and changes occurring in the nuclear stockpile as it ages.

At present, we are supporting the Los Alamos Dynamic Experimentation (DX) Division in experiments to measure the properties of materials, including plutonium, under dynamic conditions. An example of these experimental efforts is discussed in detail in the research highlight "The Reaction-History Archive" in Chapter 2.

Above-Ground Experiments

In support of the Weapons Program's above-ground experiments (AGEX-1), we have been developing diagnostics to study the physics of high-pressure shock waves. Among the diagnostics currently under development or currently fielded are

- visible-wavelength and infrared pyrometers to determine the temperature history of the back surface of a shocked material under conditions where this surface either releases into free space or is tamped by an anvil;
- low-energy x-ray sources for imaging of shock-produced low-density material (ejecta); and
- a technique for measuring the speed at which moving, high-density material can produce a fiber-optic signal.

We anticipate development of several other techniques to study material phases, including

- a very-short-pulsed laser and an ultrafast streak camera to determine by either second harmonic generation or reflectivity whether the surface of a shocked sample has melted and
- an x-ray-diffraction technique to measure phase changes at the surface of a shocked sample.

These diagnostics will be used to study shocks produced by explosives, flyer plates, gas guns, and the Atlas capacitor bank.

In other AGEX-1 work, we are supporting the development of the Dual-Axis Radiographic Hydrotest Facility (DARHT) by studying the beam physics of DARHT's prototype, THOR. We have built and successfully fielded a magnetic spectrometer to measure the beam energy as a function of time, and we have fielded a microwave interferometry diagnostic to nonintrusively measure the beam electron density and properties of the expanding target plasma created in the interaction of the electron beam and bremsstrahlung converter. We are also participating in the development of new nonintrusive beam diagnostics for the 2-μs injector of the DARHT second axis.

High-Energy-Density Hydrodynamics

The High-Energy-Density Hydrodynamics (HEDH) program has conducted several experiments of interest to the weapons community at the 4.6-MJ Pegasus II pulsed-power facility. Experiments were performed to investigate a wide range of phenomena, including nonsymmetrical hydrodynamic flow, the behavior of materials undergoing large strains at high strain-rates, frictional forces at interfaces with differential velocities on the order of kilometers per second, instability growth at interfaces in materials with and without material strength, and ejecta formation of shocked surfaces. In addition, we have pursued pulsed-power research on liner stability, current joints, and power-flow channels to ensure optimal performance for the newly constructed Atlas facility and for advanced, high-current, explosive pulsed-power systems. P-22 has already provided pulsed-power and diagnostic expertise to Procyon, Ranchito, and Ranchero, the Laboratory's existing high-explosive pulsed-power systems.

P-22 is the operations group for Atlas, the next-generation, 23-MJ pulsed-power facility. Atlas will provide advanced equation-of-state, material property, and hydrodynamic capabilities for weapons-physics and basic research. The Atlas machine and its construction are described in detail in the extended P-26 group description in this Progress Report.

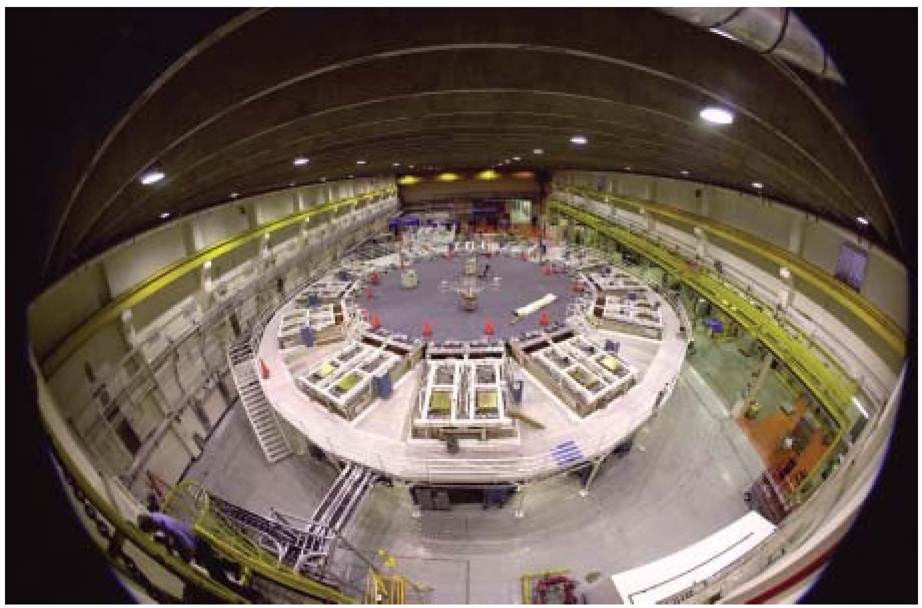


Figure 2. A "fisheye" view of the completed Atlas machine. The 24 maintenance units sit in 12 oil-filled tanks which are arranged in a circular formation around the central stage that holds the experimental target chamber.

In another part of the HEDH program, P-22's plasma-physics expertise and ability to do large-scale integrated experiments have provided group members with the opportunity to participate in several collaborations with the premier All-Russian Institute of Experimental Physics at Arzamas-16 (VNIIEF), the weapons-design laboratory that is the Russian counterpart to Los Alamos. In addition to giving us the chance to learn about some of the Russians' unique capabilities, the collaborations provide Russian weapons designers with an opportunity to do peaceful basic scientific research and to integrate themselves into the world's broader scientific community. These collaborations are based on our mutual interests in high-explosive-driven pulsed power, wherein the Russians have clearly demonstrated scalability to large systems that is, to date, unmatched in the United States. P-22 is participating in several major collaborative efforts, including

- experiments on the Russian MAGO (magnetic compression of a fusion target [in Russian]) system, a possible candidate for magnetized target fusion;
- attempts to convert a frozen rare gas to a metal by compressing it in a large magnetic field;
- the design and testing of a thin, imploding cylinder for a megajoule x-ray source; and
- studies of the properties of materials at cryogenic temperatures in magnetic fields up to 1,000 T.

We are continuing to perform integrated and fundamental radiation hydrodynamic experiments using laser- and z-pinch-driven radiation sources at the Omega and Z pulsed-power facilities at the Institute for Laser Energetics at Rochester and Sandia National Laboratories, respectively (see Figure 3). We have developed diagnostics for measuring radiation flow, including x-radiography, VISAR (velocity interferometer system for any reflector), gated x-ray imagers, filtered x-ray diodes, a curved-crystal spectrometer for stimulated fluorescence spectroscopy, and both active and passive shock breakout techniques. Our investigations have examined integrated experiments to understand radiation flow and to evaluate the usefulness of dynamic hohlraum radiation sources for a variety of future applications.

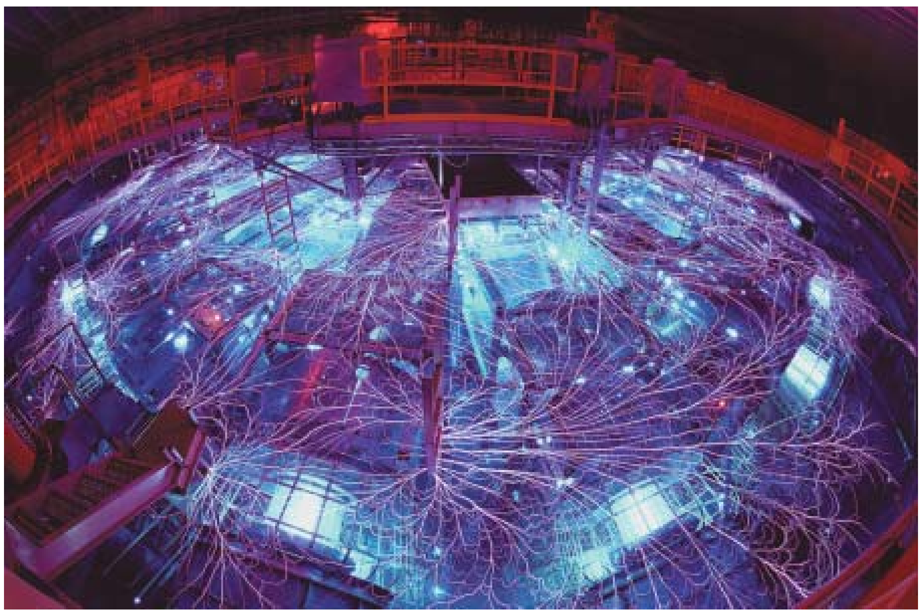


Figure 3. The Z pulsed-power machine photographed as it is firing. Radiation experiments on the Z machine have set records for machine performance and provided a basis for weapons-physics experiments in support of science-based stockpile stewardship.

Future Directions

We anticipate a lot of exciting developments in the coming years. As the operators of the Atlas facility we have a role in the facility improvements, technology development, experimental design, and diagnostic development. In addition, we will focus on diagnostic development to support upcoming experiments at NTS and other AGEX-1 facilities.

Further Information

For further information on all of P-22's projects, refer to the project descriptions in Appendix A. Some of our major achievements are also covered as research highlights in Chapter 2. These include our work in the area of fusion research, iron spallation, and the reanalysis of archival NTS data.

P-23: Neutron Science and Technology

Mary Y. Hockaday, Group Leader
R. Doug Fulton, Deputy Group Leader
Jeff Schinkel, Deputy Group Leader

Introduction

The Neutron Science and Technology Group (P-23) carries out a wide-ranging program of fundamental and applied research in weapons physics, nuclear physics, and quantum-information science. The common feature of this diverse set of efforts is the application of state-of-the-art techniques in particle and light detection and the recording of transient events.

Within the arena of weapons physics, we contribute to Laboratory programs in stockpile stewardship (SS) by participating in the design and fielding of subcritical experiments (SCEs), hydrodynamic experiments, and the reanalysis and archiving of data from past nuclear-weapons tests. Our fundamental research focuses on nuclear and weak-interaction physics and on state-of-the-art measurements of astrophysical phenomena such as solar neutrinos and ultra-high-energy gamma rays. Applied research includes the development of quantum-information technologies, such as quantum computation and encryption, the application of imaging and neutron technologies to problems relevant to national defense and industry, and participation in the accelerator production of tritium (APT).

We conduct our research at local facilities such as the Los Alamos Neutron Scattering Center (LANSCE), Milagro (see Figure 1), and local high-explosive firing sites, as well as at remote facilities like the Nevada Test Site (NTS), the Sudbury Neutrino Observatory (SNO), Fermilab, and Brookhaven National Laboratory. All of these facilities are world class, offering the best available resources for our research. Of these facilities, only the Milagro gamma ray observatory is owned and operated by P-23.

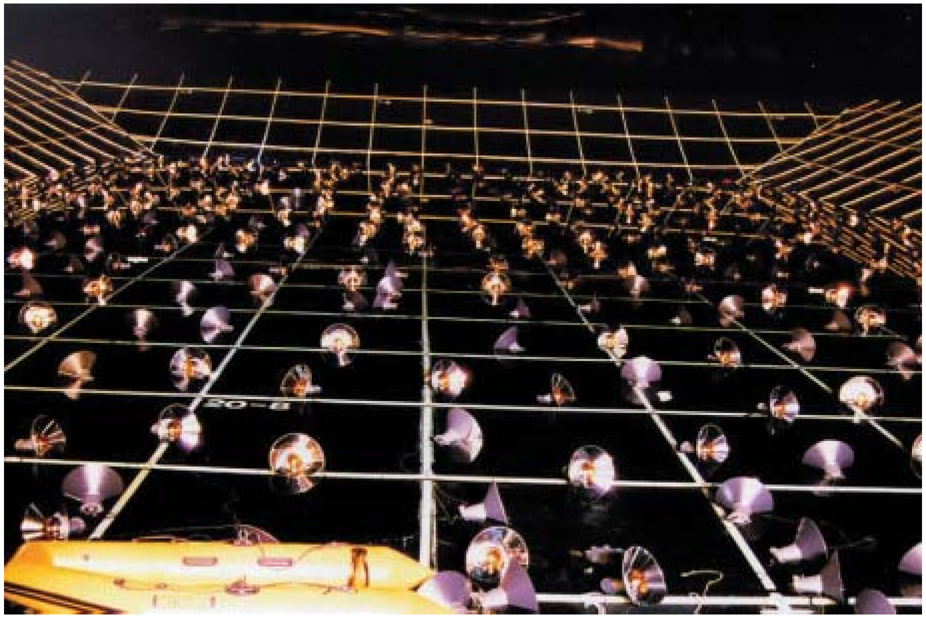


Figure 1. The Milagro detector is comprised of 723 photomultiplier tubes situated in a 5,000-m^2, 8-m-deep pond at an altitude of 8,700 ft. The photograph shows the pond before it has been filled with water, which will allow the Kevlar-bound photomultiplier tubes to extend towards the sky. Milagro has detected the particle showers produced by very high-energy gamma rays as they enter the atmosphere.

Weapons Physics and Stockpile Stewardship

With the end of nuclear testing, SS has become the foundation of the Los Alamos nuclear-weapons program. Our knowledge of how nuclear weapon systems perform relies on data obtained from tests at the NTS and test locations in the Pacific Ocean. Preserving, analyzing, and documenting NTS weapons test data is crucial to the success of SS. P-23 shares responsibility for preservation and reanalysis of these data with other groups involved in these tests. In P-23, physicists and engineers who performed the original measurements are working to reanalyze and correlate the data derived from different events. In addition, new scientists, with no previous test experience, are learning the techniques of making such measurements in case the need should arise for future underground tests.

The work of the group concentrates on analysis of Pinhole Neutron Experiments (PINEX) imaging data and on neutron emission measurements from Neutron Experiments (NUEX) and Thresholded Experiments (THREX). New methodologies using improved analytical techniques are being applied. These data complement the reaction-history and radiochemical measurements made by other groups. As a whole, this research has provided a better understanding of the underlying physical processes, and the comparison of results from different tests has allowed us to systematically study the behavior of nuclear explosives.

To ensure the success of SS in enabling us to certify the performance of our nuclear weapons in the absence of nuclear testing, P-23 is striving to develop better physics models that can be incorporated into computer codes to calculate explosive performance. Providing the community with rigorously analyzed and certified NTS data will allow the validation of the new Accelerated Strategic Computing Initiative (ASCI) codes thereby enabling the design community to address with confidence the issues of aging and remanufacture of our stockpile weapons.

In addition to the reanalysis of historic NTS data, P-23 is participating in a series of experiments to explore weapons physics issues of a more microscopic nature. In these experiments, we use chemical explosives and gas guns to create the pressures and velocities relevant to weapons physics regimes and examine issues such as the equation of state of shocked materials, formation and transport of ejecta from shocked surfaces, and growth of hydrodynamic instabilities. Our work includes a series of underground SCEs involving plutonium at the U1a facility at the NTS. These experiments employ a wide range of technologies, including gated visible imaging, gated x-ray imaging, holography, and infrared temperature measurement, to explore the physical phenomena. P-23 is currently developing two new technologies: fast infrared imaging technology, which will provide the ability to study freeze-frame dynamic motion in the infrared range, and ellipsometry to understand the dynamic emissivity of shocked matter. The data from these experiments will permit a better understanding of the hydrodynamics of interest to the weapons program and will allow us to benchmark developing models for the ASCI program.

Other weapons program work focuses on the phenomenology of weapons performance as components age. Nuclear tests and other previous weapons experiments did not address this issue, and the data from these tests are not sufficient to assure the safety and reliability of the nuclear-weapons stockpile without nuclear testing. The SS program is intended to provide a scientific basis for addressing this and other assurance issues without nuclear testing. As part of this effort, we have joined colleagues in other groups and divisions at Los Alamos National Laboratory, as well as from the Lawrence Livermore National Laboratory, to study the following issues:

- the performance of chemical explosives, including changes in performance as they age;
- the fundamental physics of plutonium and surrogate materials; and
- the characteristics of materials undergoing shock.

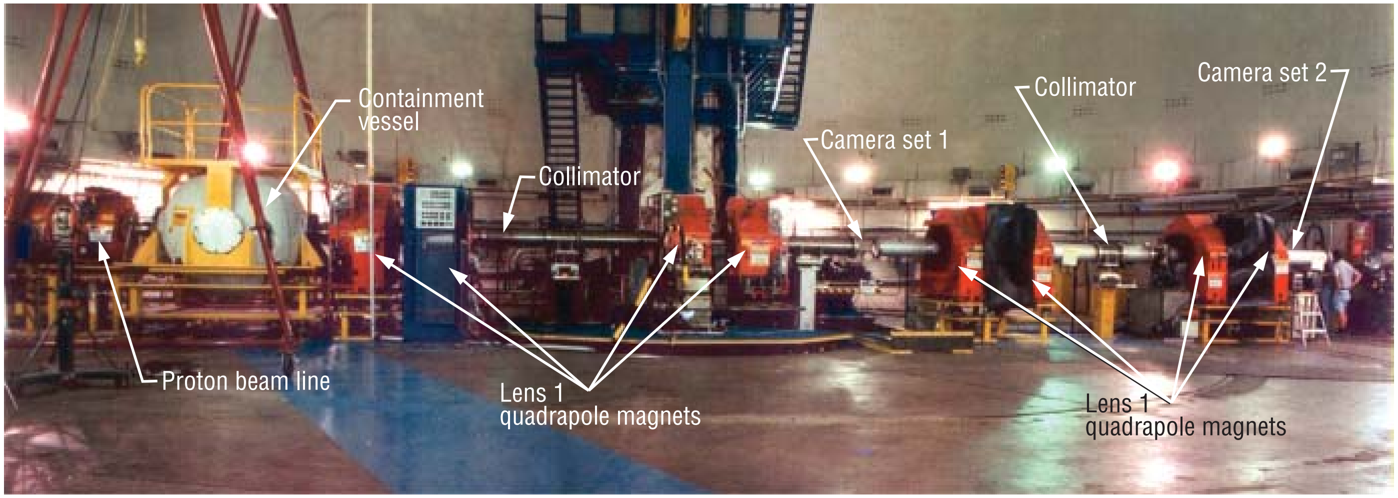
For these studies we use neutrons and protons from LANSCE sources, including protons directly from the linear accelerator, moderated neutrons from the Manual Lujan, Jr., Neutron Scattering Center (MLNSC), moderated neutrons with tailored time-structure from the Weapons Neutron Research (WNR) Blue Room, and unmoderated neutrons from the WNR fast-neutron source.

Neutron resonance spectroscopy (NRS) is a technique that uses Doppler-broadened neutron resonances to measure internal temperatures in dynamically loaded samples. In 1999–2000, P-23 worked with LANSCE operations to obtain an order of magnitude more neutrons than is possible using the MLNSC production target, thereby enhancing the utility and accuracy of the technique. In addition to temperature measurements, P-23 carried out preliminary measurements for future experiments that will measure the temperatures attained at frictional interfaces and in the "dead zones" of detonated chemical explosives. Finally, on a beam line at the MLNSC production target, we performed a series of static measurements that demonstrate that NRS can provide important information about the detailed distribution of individual constituents of uranium-niobium alloys (see the detailed research highlight "Neutron Resonance Spectroscopy: The Application of Neutron Physics to Shock and Material Physics" in Chapter 2).

An important element of the SS program at LANSCE is proton radiography (P-RAD). P-23 is working as part of the radiography project by developing and fielding imaging systems and advanced detector systems (see Figure 2). The charge coupled device (CCD)-based camera system with fast gating developed by P-23 over the report period is now capable of producing 16 high-quality time-separated images. The group has also collaborated with the Subatomic Physics Group (P-25) in the development of a pixilated, gas-amplification wire-chamber detector for proton radiography. The group continues to work with Applied Physics (X), Dynamic Experimentation (DX), and Atomic Weapons Establishment (United Kingdom) colleagues to design and optimize P-RAD experiments that are relevant to SS in a variety of weapons-physics areas including implosion physics, high-explosive performance, materials dynamics, and integrated hydro experiments (see the detailed research highlight "Proton Radiography" in Chapter 2).

The demands of the weapons program for advanced imaging technologies continue to increase. P-23 is building on its in-house capability that was developed for underground testing to meet this need. This includes the development of the GY-11 camera system, which has the capability to record up to 4000 frames per second. In addition, P-23 has investigated different technologies that will provide needed infrared cameras and pixilated detector technology for P-RAD.

Figure 2. Photograph of the Line C proton radiography system.



Accelerator Production of Tritium

P-23 contributes to the APT program by performing integral tests of the calculated neutronic performance of benchmark systems, developing beam diagnostics, and participating in irradiation studies of components for this program. Integral tests employ small-scale mockups of the accelerator target and the neutron-reflecting blanket. These allow the total neutron production, target heating, and intermediate steps to be quantified and compared with calculations. Other, advanced beam diagnostics use P-23's imaging capabilities.

Nuclear Research

As a follow-on to our work in parity violation in heavy nuclei, we are developing an experiment to measure parity violation in the np system. This experiment will attempt to measure an asymmetry of order 10^{-8} in the angular distribution of gamma rays emitted after capture of polarized neutrons by protons in a liquid-hydrogen target. A one-tenth scale experiment has been fielded at MLNSC indicating that the experimental systematic errors are indeed at the predicted low level and that a 10% measurement can be achieved (see the detailed research highlight "Measuring the Weak Nuclear Force between Protons and Neutrons" in Chapter 2). We are also working with our LANSCE colleagues to design and build a dedicated nuclear physics beam line for which the $n+p \rightarrow d+\gamma$ experiment will be the first of many.

We are also active in other tests of fundamental symmetries by observing the beta decay of trapped atoms and of free neutrons. Sensitive tests of the parity-violating beta-spin asymmetry correlation in the decay of rubidium-82 constitute one experimental sequence that we anticipate will yield results with a precision one order of magnitude greater than any previous experiment (see the detailed research highlight "Beta Decay of Rubidium-82 in a Magnetic TOP-Trap" in Chapter 2). We have observed the first parity violating beta decay asymmetry ever observed using trapped radioactive atoms. We also are designing and building an experiment to measure the asymmetry in the beta decay of polarized ultracold neutrons (UCNs) using a novel UCN source concept that has been developed at the Laboratory over the past two years.

UCNs were first produced at LANSCE in 1996 by the use of a rotor reflector. Alternative methods for producing even greater UCN densities were investigated. A cryogenic stand-alone source was built and tested in 1999 and again in 2000. The results were such that we achieved a world record 120 UCN/cm^3, three times greater than the 40 UCN/cm^3 set by Institut Laue Langevin located in Grenoble, France. Further development could provide a world-class source at LANSCE that would open up new opportunities for experiments in fundamental physics and the possibility of novel applications to materials science (see the detailed research highlight "A New Ultra-Cold Neutron Source for Fundamental Physics Measurements at LANSCE" in Chapter 2). We are also doing research and development aimed at an experiment to measure the neutron electric dipole moment (EDM) using UCNs produced and stored in a bath of superfluid helium-4. Both the EDM and the beta decay asymmetry measurements aim at detecting physics beyond the standard model of strong and electroweak interactions.

Another area of basic nuclear research is the Milagro project. Very high-energy gamma rays from the cosmos can be detected by the air shower of particles they produce when they enter the atmosphere. The Milagro project, located in the Jemez Mountains above Los Alamos, involves the operation of a high-efficiency observatory for gamma rays in the energy range around 10^{14} eV. This observatory is a joint project involving Los Alamos and a large number of universities and is sponsored by the Department of Energy (DOE) Office of Nuclear Physics, the DOE

Office of High Energy Physics, and the National Science Foundation (see the detailed research highlight “High-Energy Gamma-Astronomy with Milagro” in Chapter 2). It is well-suited for the study of episodic or transient gamma-ray sources—that is, for recording gamma-ray bursts. Milagro is operational 24 hours a day, 365 days a year, and its field of view is nearly half of the sky. Milagro was completed in 1999. The gamma-ray shadow of the moon and gamma emission from the Crab Nebula have been observed. We have also observed a possible Gamma Ray Burster with Milagro.

We are also involved in ongoing research of the properties of solar neutrinos. The number and energy spectrum of neutrinos from the sun continues to challenge our understanding of solar physics and neutrino properties. We are collaborating in the development of SNO, a neutrino observatory more than a mile underground in Sudbury, Ontario. The SNO detector became operational in 1999 and consists of an acrylic vessel holding 1,000 tons of heavy water surrounded by another vessel with 8,000 tons of light (regular) water. All three flavors of neutrinos (electron, muon, and tau) have been detected. Development of this detector includes the design and fabrication of very-low-background helium-3 detectors and new electronics. As a spin-off, the very sensitive, low-background detectors developed for the observatory will be used to screen high-density microelectronics for trace radioactive contaminants that can cause computer errors by “flipping” bit patterns. The first physics results were reported at the Neutrino 2000 Conference, and Los Alamos played a critical role in the analysis.

Applications of Basic Research

Quantum computation promises a new approach to solving some problems regarded as intractable in classical computation by using the quantum-mechanical superposition of many states (numbers) at once. To realize such a computer, we have continued our work in developing a system with cold, trapped atoms that can be put into the desired quantum-mechanical states (for more information see the research highlight “Quantum Information Science” in Chapter 2). Quantum logical operations are performed via laser manipulation of the states of the trapped atoms. Using conventional lasers, we have recently succeeded in trapping and imaging calcium ions that have the required spectroscopic structure to allow them to serve as basic quantum-mechanical bits. We have succeeded in trapping a string of 15 atoms.

Our applied research also includes work in quantum cryptography, which is covered in a detailed research highlight “Quantum Information Science” in Chapter 2. Quantum mechanics provides an approach to unbreakable cryptographic codes that not only can transmit the code “key” with security but that can also reveal the presence of eavesdropping. We hold the world record for a fiber-based quantum cryptography system and are developing longer transmission demonstrations. In a related effort, we have demonstrated transmission of a “key” through 1.65 km of air (see Figure 3). Presently we are looking towards establishing secure communications between ground-based stations and low-Earth-orbit satellites.

We have developed a novel light source for producing polarization-entangled photon pairs. These are quantum-mechanical states in which the polarization of an individual photon is random, but is nevertheless perfectly correlated with the polarization of its partner photon. This source of entanglement has allowed us to study a variety of quantum mechanical phenomena, including a world-record-setting test of quantum nonlocality, the first experimental investigation of “decoherence-free subspaces,” and the first demonstration of entangled-photon quantum key distribution. In the future, we plan to develop this technology for use in the field to perform demonstrations of quantum-encrypted communications over multikilometer atmospheric paths. We also support Department of Defense (DOD) programs in mine detection and seeker applications. P-23 has developed a laser-based, range-gated imaging system for the airborne detection of submerged mines. The system has undergone testing in both controlled-tank and open-sea environments. We have supported seeker (target identification) programs with range-gated laser distancing and ranging (LADAR) experiments carried out at the Wright Laboratory's laser range at Eglin Air Force Base. These experiments are part of a joint DOE/DOD technology-development program.

Further Information

To learn more about the projects described here, as well as other projects within P-23, refer to the project descriptions in Appendix A. Some of our major achievements are also covered as research highlights in Chapter 2, as mentioned above. These include our work in quantum information, ultra-cold neutrons, fundamental symmetries with magnetically trapped rubidium-82 and the np system, neutron resonance spectroscopy, Milagro, and nuclear test data and science.

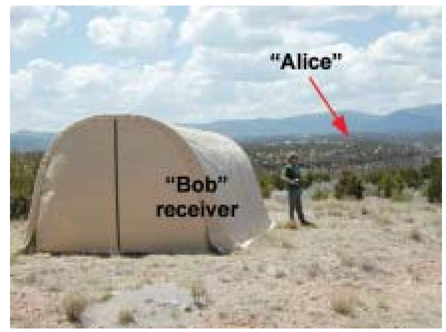


Figure 3. One of the goals of cryptography is for two parties ("Alice" and "Bob") to render their communications unintelligible to a third party. Quantum key distribution (QKD) can create "key" material whose security is assured by the laws of quantum mechanics. The "free space" quantum cryptography experiment successfully transmitted a usable cryptographic key over 1.6 km across a test range in full daylight.

P-24: Plasma Physics

Kurt F. Schoenberg, Group Leader
Juan C. Fernández, Deputy Group Leader

Introduction

The Plasma Physics Group (P-24) researches the basic properties of plasmas with a view to applications in important Los Alamos National Laboratory and national programs. Plasmas occur in nature when matter exceeds temperatures of roughly 10,000° C. At these temperatures, the constituent atoms and molecules of matter begin to lose their bound electrons to form a substance composed of positive or negative ions and free electrons. All principal phenomena in plasmas can be traced to the fact that ions and electrons interact with each other through long-range electromagnetic forces. The electromagnetic interactions of groups of charged particles are often coherent, leading to collective modes of plasma behavior. This collective interaction of charged particles, a many-body problem, is the essence of the field of plasma physics.

Roughly 99% of the matter in the universe is in a plasma state. Plasmas can exist over a large range of temperatures and densities. For example, interstellar space contains plasmas with densities of less than one ion or electron per cubic meter at temperatures exceeding 1,000° C. In contrast, plasmas created by intense laser compression of micropellets achieve densities up to 10^{26} ions or electrons per cubic centimeter at temperatures exceeding 10,000,000° C. The understanding and application of such diverse plasmas is a Los Alamos core competency.

P-24 is composed of a diverse technical staff with expertise in plasma physics, plasma chemistry, atomic physics, laser and optical science, pulsed power, dynamic properties of materials, and transient radiation and particle diagnostics. The group uses both on-site and off-site experimental facilities to address problems of national significance in inertial and magnetic fusion, high-energy-density physics, conventional defense, environmental management, and plasma-based advanced or environmentally friendly manufacturing. Our agenda includes basic research in the properties of energetic matter and applied research that supports the principal Laboratory mission of enhancing global nuclear security. The pursuit of this agenda entails the physics of plasmas over a wide and diverse range of conditions, as shown in Figure 1.

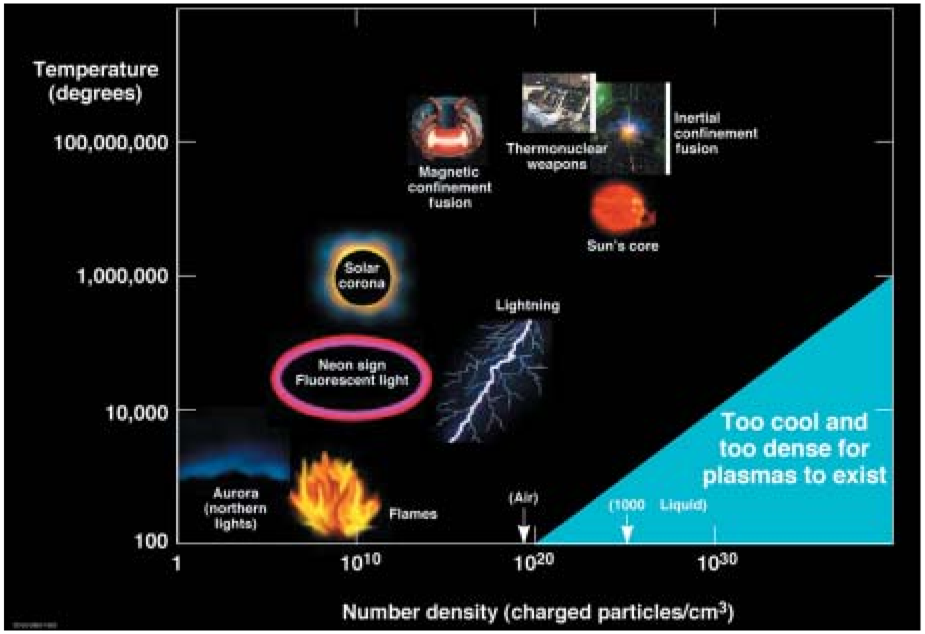


Figure 1. As this illustration of the plasma state shows, the physics of plasmas entails a wide and diverse range of conditions. (Illustration courtesy of Dr. Don Correll, Lawrence Livermore National Laboratory).

Trident Laser Facility

Trident is the multipurpose laboratory at Los Alamos for conducting experiments requiring high-energy laser-light pulses. As a user facility, it is operated by P-24 primarily for inertial confinement fusion (ICF) research, high-energy-density physics, and basic research. Features include flexible driver characteristics and illumination geometries, a broad resident diagnostic capability, and flexible scheduling. A dedicated staff maintains and operates the facility and assists visiting experimenters. Target fabrication is supported by the Laboratory's Target-Fabrication Facility in the Materials Science and Technology (MST) Division.

The principal resource at Trident is the laser driver (Figure 2). It employs a neodymium-doped, yttrium-lithium-fluoride (Nd:YLF) master oscillator and a chain of Nd:phosphate glass-rod and disk amplifiers in a conventional master-oscillator, power amplifier architecture. The oscillator output pulse is temporally shaped, amplified, split into two beams, amplified again, frequency-doubled, transported, and focused onto the target. A third beam line can be used as an optical probe or to provide an x-ray backlighting capability. Its pulse can be either 100 ps in length or the same length and shape as those of the main drive beams. Although the third beam line is normally operated at 527 nm, it can also be operated at 1,054 nm or 351 nm (fundamental and third harmonic output, respectively). The third beam can be timed to become active before or up to 5 ns after the main drive beams. The output of the master oscillator may also be frequency-broadened and "chirped" before amplification to allow compression to subpicosecond pulse lengths. Although normal operation relies on pulse lengths of order 1 ns, pulse lengths for specialized applications (such as dynamic materials experiments) have exceeded 100 ns.

Figure 2. Laser driver of the Trident laser facility.

The south high-vacuum target chamber is a cylinder approximately 150-cm long and 75 cm in diameter. Single- or double-sided illumination of targets is possible through several 20-cm-diameter ports on each end of the chamber. More than 40 smaller ports are available for diagnostic instrumentation. Individual targets are inserted through an airlock. The target insertion and positioning mechanism provides *x-y-z* and rotation adjustment under computer control with 1-μm linear and 0.01° angular resolution. The three-axis target-viewing system has a 20-μm resolution. The chamber is fitted with a Nova standard six-inch instrument manipulator (SIM) to accept all SIM-based instruments for checkout, characterization, or use. Trident is located in an area of the Laboratory that can accommodate both unclassified and classified research.

The north high-vacuum target chamber has just become available for experiments. It is a spherical stainless steel chamber, 3" thick and 63.25" outside diameter. It is capable of very flexible target illumination and diagnostic placement due to the 92 ports of various sizes available around the chamber surface. At present, laser illumination at the north chamber is available at 1,054 nm only, but the beam transport and alignment systems for 351 nm are being designed. The chamber has just been fitted with a brand new diagnostic manipulator of the latest generation: the ten-inch instrument manipulator (TIM) in use at the Omega laser facility at the University of Rochester. The TIM can also accept the earlier-generation SIM-based instruments. We also have in house the prototype for the diagnostic insertion manipulator (DIM) for the National Ignition Facility (NIF), designed and built in the United Kingdom (UK) by the Atomic

Weapons Establishment (AWE). In the near future it will be mated to the north chamber to allow the ICF community to test DIM-based NIF diagnostics, a unique capability that Trident will provide.

Optical diagnostics routinely used at Trident include illumination and backscattered-light calorimeters, backscattered-light spectrometers, and high-bandwidth (5-GHz) and streak-camera-based power monitors. Target x-ray emission is monitored by filtered, photoconductive diamond detectors and an x-ray streak camera with <10-ps resolution. Gated, filtered x-ray images covering 1 ns in 16 images are provided with 80-ps resolution by a SIM-based standard gated x-ray imager. Various filtered x-ray power and spectral diagnostics can be installed as needed. These cover the energy range of 0–35 keV. Static x-ray pinhole cameras are also available. Both point and line VISAR (velocity interferometer system for any reflector) diagnostics are now being used for selected experiments. Most optical and target diagnostics are available for either the main target chambers or the ultrahigh-irradiance chamber.

As a user facility, Trident is available to both Laboratory and outside experimenters. The quality of proposed research and its relevance to Laboratory missions are major criteria in determining what experiments are fielded. Trident is operated by P-24 as a user facility that principally supports the Inertial Confinement Fusion and Radiation Physics (ICF&RP) program as well as other programs in the Nuclear Weapons Directorate. It is funded through and operated for the ICF&RP Program Office. The resources of the Laboratory's Target-Fabrication Facility, operated by MST Division, are also available to assist experimenters in designing, fabricating, and characterizing targets for Trident experiments.

In the long term, we intend to upgrade the Trident laser using refurbished Nova laser components, contingent on available funding. This upgraded laser system would be based on a multipass architecture with Nova 31.5-cm disk amplifiers. This new laser system would eventually include eight beam lines operating at 700 J each in 1 ns at 351 nm. Trident, in both its present and upgraded configurations, is envisioned to remain a very flexible, high-shot-rate facility that provides a staging capability to higher energy facilities such as Omega, the future NIF, and the Z pulsed-power machine at Sandia National Laboratories (Sandia). It will also allow us to continue performing experiments in laser-matter interactions and other fundamental science topics, and it will serve as an attractor for high-quality scientific research relevant to ICF and stockpile stewardship.

Inertial Confinement Fusion

The ICF&RP program at Los Alamos is a principal component of the national ICF program. A principal focus of the national program is the goal of achieving thermonuclear ignition in the laboratory, one of the grand scientific challenges of our time. This goal is part of the broader mission to provide scientific knowledge, experimental facilities, and technological expertise to support the Department of Energy (DOE) Stockpile Stewardship Management Plan for nuclear weapons. In pursuit of the ICF mission, P-24 designs, diagnoses, executes, and analyzes the results from experiments at high-energy laser facilities worldwide. P-24 partners with other Los Alamos groups that focus on theory, modeling, and target fabrication to execute the program, with the ultimate goal of understanding laser-matter interaction physics.

NIF is a state-of-the-art laser facility presently under construction at Lawrence Livermore National Laboratory (Livermore) (see Figure 3), at a cost of billions of dollars. It will be the world's most powerful laser by far and the principal focus of the national ICF program. Los Alamos and Sandia have been participating with Livermore in the design and construction of special equipment for this immense laser facility, which will be ≈300 ft × 500 ft upon completion and operate at an energy of 1.8 MJ at a major wavelength of 351 nm.

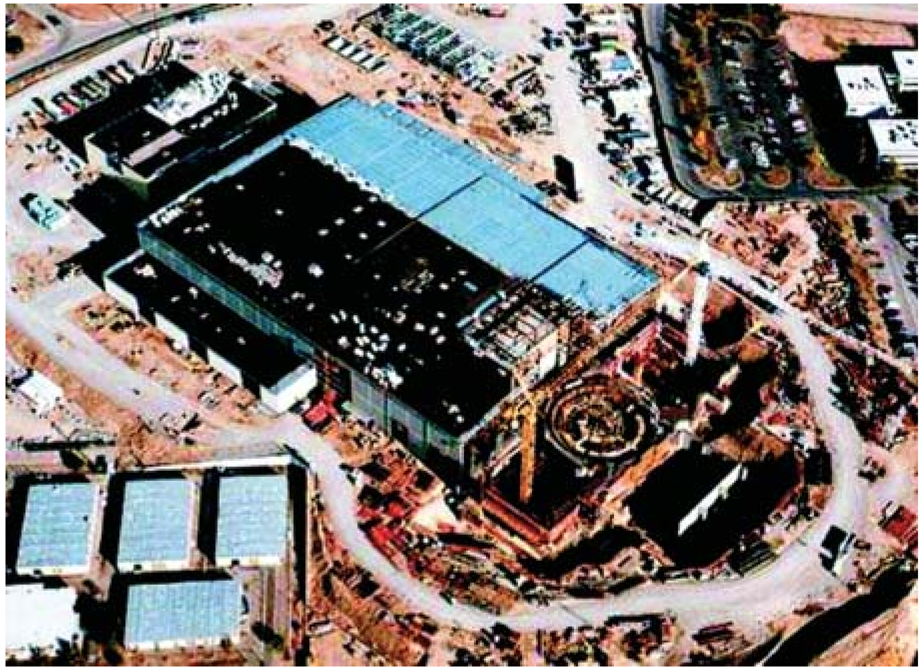


Figure 3. Arial view of the National Ignition Facility, a state-of-the-art, $1.2B laser facility presently under construction at Lawrence Livermore National Laboratory. The facility will be a key component in the national ICF program, which aims at achieving thermonuclear ignition in a laboratory setting.

In the early 1990s, Los Alamos scientists collaborated with other members of the national ICF program to establish the functional requirements and primary criteria that are the basis for this facility. Los Alamos scientists and engineers have been participating since fiscal year 1993 in the conceptual, preliminary, and detailed designs of a variety of NIF subsystems. P-24 is also a principal participant in the NIF Joint Central Diagnostic Team, and P-24 personnel have worked on the conceptual design for the 351-nm power and energy diagnostics, the preliminary design of a time-resolved x-ray imaging system, and various radiation and particle diagnostics of fusion. In addition, P-24 personnel have been involved with the management of this collaborative project.

NIF is a flexible laser, capable of greatly advancing both the ignition and weapons-physics missions. NIF is designed to drive a capsule filled with deuterium-tritium fuel to thermonuclear ignition by one of two distinct methods: direct or indirect drive. Direct drive involves the implosion of a capsule that is directly illuminated by the laser beams. Indirect drive involves laser illumination of the interior walls of a cavity (called a hohlraum) that contains the capsule. The hohlraum converts the laser energy into x-rays, which illuminate and implode the capsule very symmetrically, analogous to the process of baking an object evenly in an oven. Because both methods have different potential failure modes, both are being pursued to increase the likelihood of achieving ignition on NIF.

Considerable challenges face us in preparation for achieving fusion ignition on NIF, which will first be attempted using indirect drive. These challenges include developing novel diagnostic methods and instruments and improving our understanding in several scientific areas, including laser-plasma instabilities, hydrodynamic instabilities, hohlraum dynamics, and dynamic properties of materials. P-24 has contributed significantly in all of these areas with target-physics experiments using present and past lasers: Nova at Livermore, Omega Upgrade at the University of Rochester, and Trident at Los Alamos. For selected dynamic materials experiments, P-24 is also making use of the Z facility at Sandia.

P-24 personnel have devoted considerable effort over time to studying laser-plasma parametric instability (LPI) processes. We are focused presently on stimulated Raman scattering (SRS) and on the novel phenomena of beam deflection by plasma flow. LPIs pose a significant threat to ignition hohlraums because they could potentially scatter most of the laser light, decreasing both the drive efficiency and the capsule-illumination symmetry. In the recent past, P-24 has pursued a dual-track strategy of complementary experimental campaigns at Nova and Trident. P-24 researchers have applied the extensive Nova diagnostic suite on ignition-relevant hohlraums designed at Los Alamos, the most NIF-like plasmas ever made. The LPI experiments on Nova are now complete, and much of the data analysis has been finished and published. For more information, please read the research highlight "Laser Plasma Interactions in a Single Hot Spot" in Chapter 2. The resulting extensive LPI database has been invaluable in framing the important physics issues, guiding theoretical modeling and further experiments.

Our LPI experimental thrust has shifted to the application of new state-of-the-art capabilities and diagnostics on Trident long-scale NIF-relevant plasmas to allow more detailed measurements and comparisons of theory with experiment. These new capabilities include a nearly diffraction-limited interaction beam capable of the intensity range relevant to parametric instabilities in ignition-hohlraum plasmas. The use of a diffraction-limited interaction beam has proven to be a new paradigm in LPI experiments. It has allowed a whole new class of experiments where the results can be interpreted unambiguously to differentiate alternative theoretical possibilities, which is impossible when a conventional, speckled laser beam is used for interaction experiments. Imaging Thomson scattering now yields direct measurements of the spatial profile of important plasma parameters, such as electron density and temperature, ion temperature, plasma-flow velocity, and the location of the electrostatic waves responsible for laser scattering. We now can thoroughly benchmark the radiation-hydrodynamic codes used to design the plasma conditions in the first place.

The coupling of these recent diagnostics with reflected and transmitted beam diagnostics has allowed unprecedented studies of the time evolution of parametric instabilities and beam deflection. For example, in the context of our beam deflection experiments, Trident has provided (to our knowledge) the first quantitative detailed comparison between modeling and experiment on laser filamentation, to find that fluid plasma modeling coupled to an appropriate heat conduction model are sufficient to describe the phenomenon. We are exploiting the fact that the single-hot-spot Trident system is sufficiently small for direct modeling by an emerging suite of codes incorporating new theoretical models. At this point, for example, we know that kinetic effects are necessary to understand the evolution of SRS in long-scale NIF-relevant plasmas. Using kinetic models, a prediction for a new type of back-scattering process was verified experimentally. Ultimately we hope to gain sufficient understanding to develop simplified "reduced-description" models that are suitable for NIF-scale plasmas.

P-24 personnel have had important successes in advancing our understanding and capabilities in hohlraum dynamics. Based on experiments we have fielded in the recent past, we have become fairly confident in our understanding of the capabilities of cylindrical hohlraums, which will be used in the first indirect-drive ignition attempts on NIF, provided that we stay away from the regime of strong laser backscattering due to parametric instabilities. On Nova, we demonstrated control of beam deflection and its effects on capsule-illumination symmetry by spatial smoothing of the laser beam. On Omega Upgrade, we collaborated with Livermore researchers in an important experimental series that exploited the larger number of Omega beams to demonstrate the use and understanding of "beam phasing," in which beams are arranged into multiple beam cones, forming multiple rings of beam spots on the inner surface of a cylindrical hohlraum. Beam phasing will be necessary on NIF to tune both the time-integrated and time-dependent capsule-flux asymmetry by adjustment of the beam pointing and the power history in the different rings.

We have also demonstrated unprecedented time-integrated illumination symmetry using an advanced hohlraum design developed at Los Alamos for deployment at Omega Upgrade, featuring a spherical radiation case and laser-entrance holes in a tetrahedral arrangement (see Figure 4). Because the unique mission of Omega Upgrade is direct drive, the beams enter the target chamber in a spherical geometry, a nonoptimal arrangement for cylindrical hohlraums. But tetrahedral hohlraums in Omega Upgrade can use all 60 beams and drive higher energy implosions than cylindrical implosions, an added advantage to the improved symmetry. The high illumination symmetry provided by tetrahedral hohlraums has been exploited in capsule implosion experiments described below.

There has been significant activity and progress in the area of hydrodynamic instability of imploding capsules. At NIF, capsules with cryogenic fuel will have to be compressed to large convergence ratios (above 30) in order to ignite. Convergence is ultimately limited by hydrodynamic instability. Until recently, laser-driven capsule implosions have only achieved moderate convergence ratios (below 10), attributed at least in part to the known limitations of past laser systems, including Nova, that had too few beams to provide the desired capsule illumination symmetry. It was believed that once smoother hohlraum illumination became available, high-performance capsule implosions with significantly higher convergence would be straightforward to demonstrate. A series of experiments was carried out by P-24 personnel at Omega to compress capsules to convergence ratios of about 18 using tetrahedral hohlraums. In spite of the high illumination symmetry, the capsule neutron yield was degraded relative to corresponding calculations of ideal capsule implosions with no hydrodynamic mix in a manner similar to Nova capsules. These data are giving impetus to the development and testing of a novel mix model at Los Alamos.

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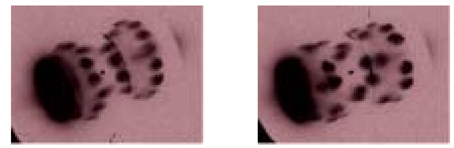


Figure 4. Cylindrical hohlraums with single-ring (a) and two-ring (b) configuration of beam spots. Experiments with such hohlraums are the first step in developing "beam phasing," in which many beams are arranged into multiple beam cones to control implosive symmetry.

P-24 hydrodynamics research has also focused on cylindrical implosion targets, which are much easier to diagnose than capsules and yet retain important convergent effects. P-24 researchers have completed a study of the nonlinear growth of multi-mode perturbations in x-ray-driven cylindrical targets due to the ablative Raleigh-Taylor (RT) instability on Nova, and the results were in good agreement with theoretical modeling. Moreover, there was spectacular success in deploying direct-drive cylindrical implosions of Los Alamos design, capable of significantly higher RT growth than the indirect-drive design. Our single-mode RT experiments on the new design showed significantly lower growth factors than predicted. A series of experiments with closely controlled but varying surface finish and imposed seed perturbations to test our theoretical understanding of these implosions is underway.

In collaboration with other groups in the Laboratory's Physics Division, Applied Theoretical and Computational Physics Division, as well as Oxford University, the University of California at San

Diego, Sandia, and Livermore, P-24 is using the Trident laser system to pursue studies of the dynamic properties of materials that are of interest to the ICF&RP program and to weapons science. The Trident laser is used to drive high-pressure (from tens of kilobars to several megabars), temporally shaped shocks into condensed materials under study. An exciting and novel alternative for driving dynamic materials experiments has been demonstrated recently on Trident. It uses a Trident beam in a relatively long pulse (>100 ns) to heat a plasma and drive smoothly a very flat flyer plate of ~2 mm diameter to velocities of a few kilometers per second. Using a flyer plate to shock materials makes a clear connection to conventional experiments in this field and avoids the potential drawbacks and questions associated with direct laser illumination of solids. Separate beams of the laser system can be used to create accurately synchronized, powerful x-ray and optical pulses that are used for probing the shocked material. Using this configuration, the group has developed and utilized novel diagnostic methods such as transient x-ray diffraction (TXD) and velocity interferometry (VISAR). TXD and VISAR have in turn been used to measure the dynamic properties of phase changes in materials. These experiments are being carried out both at Trident and at the Z pulsed-power facility, exploiting the novel capabilities for driving dynamic materials experiments recently developed there.

The experimental methods developed on Trident are being applied to materials of central interest to ICF, such as beryllium. One of the ultimate goals of this research program is detailed characterization of beryllium alloys such as beryllium-copper. These materials will be used as the ablator in advanced, Los Alamos-designed ignition capsules with superior hydrodynamic stability. Exact determination of the melt transition in these materials is crucial for predicting their hydrodynamic behavior during implosion. Initial experiments with available samples have already shown solid-solid phase transitions. Upon availability of samples with the necessary quality (including beryllium crystals), we intend to carry out a definitive study of phase transitions and melt in these materials in the pressure range of interest to ICF. Beyond phase transitions, we are studying other dynamic phenomena, such as spall, in various materials, including metals such as copper.

High-Energy-Density Experiments in Support of Stockpile Stewardship

P-24 performs laser and pulsed-power-based experiments that are intended to enhance understanding of the basic physical processes that underlie nuclear-weapons operation. In collaboration with weapons designers and other theoreticians, these experiments are designed to address issues in areas such as radiation hydrodynamics, fluid instabilities, shock-wave physics, and materials science. The experiments use the Trident laser, the Omega laser, the Helen laser at the AWE Laboratory in the UK, and Sandia's Z pulsed-power machine. We have formed strong world-wide collaborations in the disciplines central to high-energy density physics. Current work in the group includes

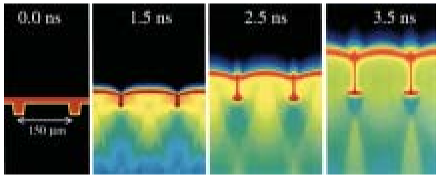


Figure 5. RAGE simulation of transverse view through the package showing the development of a 20-µm-wide spike, 30-µm tall above a 15-µm-thick back-plane CH-covered copper package at different times. The color scale represents the copper density from 0.1 g/cc in the low-density blow-off to 10 g/cc in the slightly compressed copper spikes and bubbles at 1.5 ns.

- studies of nonlinear evolution of hydrodynamic instabilities using planar and cylindrical targets driven by a variety of pressure sources (this includes the study of shock-driven turbulence using direct-laser-drive cylindrical targets at Omega);
- study of the implosion of cylindrical and spherical shells with various defects;
- topics in radiation hydrodynamics;
- imploding-liner studies of the basic nature of material friction;
- development and application of transient x-ray diffraction and other diagnostic techniques for the study of solid phase changes, plastic flow, and other materials phenomena;
- study (in collaboration with Sandia) of materials that are of interest for stockpile stewarship; and
- study of high-energy, laser-based x-ray radiography for diagnosis of hydrodynamic instability and radiation-hydrodynamic experiments.

It is worth highlighting one of these topics, which has been the subject of considerable effort in our group. We have performed a series of experiments on the Omega laser to test our predictive capability of the ablative RT instability as it evolves into the nonlinear stage dominated by thin spikes between thin bubbles. In these experiments, x-ray illumination (≈170–190 eV temperature) provided by spherical Omega hohlraums with tetrahedral illumnation symmetry have been used to accelerate planar copper targets with a preimposed perturbation. The normal difficulty with present-day facilities *(i.e.*, x-ray drive insufficient in strength and duration to drive RT beyond the linear phase) has been circumvented by imposing a nonlinear initial condition that resembles the bubble-spike structure expected in the late stages of RT evolution. The initial condition imposed on the RT target consists (in two dimensions [2-D]) of square spikes placed 150-µm apart, 30-µm high and either 10- or 20-µm wide. In reality, the spikes were ridges about 200 µm in length.

A flavor of the evolution of such a target is shown in Figures 5 and 6. Figure 5 shows a 2-D simulation with the RAGE code of the target with spikes initially 20-µm wide. Figure 6 shows experimental radiographs of the targets with spikes initially 10-µm wide. The simulation shows that the backing material flows in a way as to increase the length of the spikes. Therefore, a key figure of merit to compare between modeling and experiments is the height of the spikes above the backing surface. Our results agree qualitatively with the predictions from RAGE, but there are important differences presently under investigation. One difference is less spike growth than predicted. Another difference is that the strong predicted dependence on backing thickness is not observed.

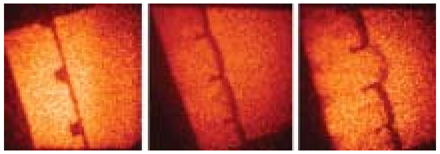


Figure 6. Radiographs taken with 6.7 keV x-rays of a driven target with spikes initially 20 µm in width and 30 µm in height above a 15-µm-thick back-plane. The target is overcoated with a 4 µm CH ablator layer of half normal density on the spike (left) side, which is the driven side. The times shown are (from left to right) 0, 2, and 3.4 ns relative to the beginning of the x-ray drive.

Magnetic Confinement Fusion

Magnetic fusion energy (MFE) research, and its associated science, is an important constituent of P-24's plasma physics portfolio. We are capitalizing on the recent strategic shift in national fusion research priorities to increase the emphasis on innovative fusion confinement approaches. To that end, we are working in P-24 with the Los Alamos MFE Program Office to develop new low-cost concepts for fusion energy. Central to this effort is MTF (magnetized target fusion), a truly different fusion concept intermediate in density between traditional magnetic fusion and inertial fusion. We specifically propose to form and preheat a compact toroid target plasma using well-established techniques and then compress this target plasma with imploding liner technology developed by DOE defense programs. A schematic of the proposed MTF machine is shown in Figure 7.

Three technical considerations explain why research in the MTF density regime is important. First, fusion reactivity, which scales as density squared, can be increased by many orders of magnitude over conventional MFE. Second, all characteristic plasma scale-lengths decrease with density. Hence,

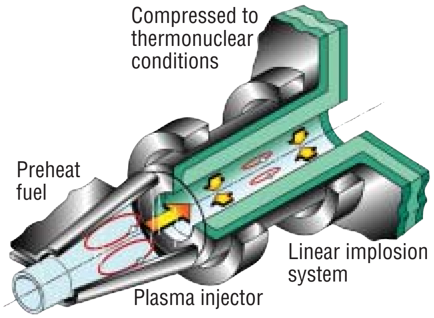


Figure 7. MTF will require us to create the initial plasma configuration, inject it axially into a flux-conserving shell, and finally compress the plasma to fusion-relevant density and temperature.

system size is naturally reduced at a high density. Third, magnetic insulation greatly reduces the required power and precision to compressionally heat a plasma to fusion-relevant conditions compared with ICF and brings the pulsed-power requirements for adiabatic plasma heating within reach of existing facilities. For more information, please read the research highlight "Magnetized Target Fusion" in Chapter 2.

The future path for engineering development of MTF as an economic power source is less well-defined than for the more mature approaches of MFE and ICF. However, a number of possibilities are being discussed, and our research program will include scoping studies to identify the most promising approaches. If successful, MTF will achieve high performance fusion conditions with soon-to-be-realized pulsed-power facilities such as Atlas.

Historically, Los Alamos has had significant involvement in developing alternate approaches to fusion. This precedent has guided our development of collaborative programs with the National Institute for Fusion Science (NIFS) (Japan), the University of Washington, Livermore, and the Princeton Plasma Physics Laboratory. In all four collaborations, we employ our engineering, physics, and diagnostics expertise to aid the development of exciting moving fusion concepts.

Our collaboration with NIFS at the Large Helical Device (stellarator) involves the development of advanced imaging bolometry diagnostics. In collaboration with the University of Washington, we developed and fielded a 100-MW amplifier to drive plasma current in a field-reversed configuration (FRC) experiment by means of rotating magnetic fields. FRCs belong to the compact toroid class of fusion approaches and promise efficient magnetoplasma confinement with simple, compact reactor configurations. Our collaboration with the University of Washington on current-drive experiments are central to the notion of steady-state FRC operation.

With Livermore we are taking the next step in sustained spheromak confinement research. The Sustained Spheromak Physics Experiment, operating at Livermore, was designed to achieve high plasma performance under quasi-steady-state conditions. Los Alamos expertise, developed over years of research on the Compact Torus Experiment spheromak, will be an important contributor to the success of this effort. We are also members of the national research team on the National Spherical Torus Experiment, operating at the Princeton Plasma Physics Laboratory. This experiment investigates the confinement properties of very low-aspect-ratio tokamaks with a view to achieving efficient (high-beta) confinement in a compact toroidal system. At the National Spherical Torus Experiment, we are focusing on fast imaging of visible light turbulence in the edge of the plasma, as well as observations of general phenomena during helicity injection current drive

Applied Plasma Technologies

P-24 develops and uses advanced plasma science and technology to solve problems in the areas of defense, the environment, and industrial manufacturing. The group has achieved international status and recognition in this pursuit in recent years, including three R&D 100 awards. The first R&D 100 award, presented in 1996, was in recognition of the development of the PLASMAX system, which takes advantage of plasma sheath properties combined with mechanical vibration to rapidly and effectively clean semiconductor wafers without water or other liquid solvents. The second R&D 100 award, presented in 1997, recognized the efforts of a multidisciplinary group (both Laboratory and industrial personnel) in the initial commercialization of plasma source ion implantation (PSII). More recently, our efforts have concentrated on the development of the atmospheric-pressure plasma jet (APPJ, described below), for which an R&D 100 award was granted in 1999 and a patent was just granted to the University of California in February 2001.

Atmospheric-Pressure Plasma Jet

A nonthermal, uniform-glow discharge at atmospheric pressure in a cylindrical cavity with high gas-flow rates produces reactive chemical radicals and metastables persisting for fractions of a second at atmospheric pressure. These reactive species remove surface contaminants and films, providing a new means of cleaning objects and substrates (see Figure 8). Current programs include chemical and biological decontamination for the neutralization of chemical agents on surfaces and graffiti removal. We have also been working on improving further the operation of the APPJ. One recent success has been the ability to decrease significantly the necessary fraction of helium in the feed gas to maintain acceptable operation. This development promises to decrease the cost of APPJ-based processing for many applications where very large surface areas are to be treated.

For more information, please read the research highlight "Materials Processing using an Atomospheric-Pressure Plasma Jet" in Chapter 2.

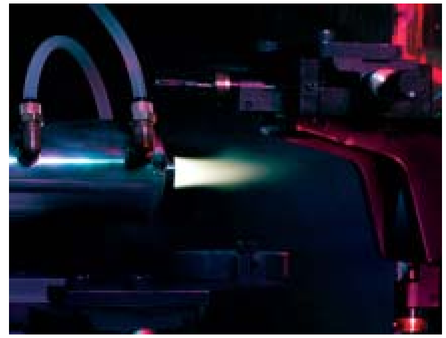


Figure 8. The atmospheric-pressure plasma jet in operation, with a reactive gas stream exiting from the source.

Atlas

Atlas is a 24-MJ, 30-MA advanced pulsed-power facility that was completed in late 2000. Now that the pulsed-power driver, the major part of the facility, has been finished, attention has shifted to completing the power-flow system that delivers the driver energy to the load (*i.e.*, the experimental packages of interest). P-24 has been involved in several aspects of the physical design of Atlas, including primary responsibility for the power-flow system. P-24 has been also involved in defining and designing the experimental agenda for the first several years of operation, developing advanced diagnostics to be fielded on these experiments, and fielding experiments on Pegasus and Ranchero to prepare for Atlas operation.

The Atlas Physics Design Team, which includes P-24 staff, has developed the list of the types of experiments to be fielded in the first 200 shots (the first two years of Atlas operation). This experimental program relies on the capability of Atlas to implode 40-g cylindrical liners at velocities of up to 20 km/s on timescales of several microseconds. Such implosions will produce material pressures of several tens of megabars, magnetic fields up to 1,000 T, material strain rates of 10^6 s^{-1}, and strongly coupled plasmas of nearly solid densities at temperatures of several electron volts. Included on this program are experiments to investigate Rayleigh-Taylor mix, Bell-Plesset deformation of the liner, friction at high relative velocities, on-hugoniot equation-of-state (EOS) measurements, calibration of the Nevada Test Site nuclear impedance-matching EOS experiments, multiple-shock EOS, quasi-adiabatic compression of materials, release isentropes, high-strain-rate phenomena, dense-plasma EOS and transport, hydrodynamics and instabilities in strongly coupled plasmas, magnetized target fusion (MTF), and high magnetic field generation. Specific experimental campaigns are now being designed to determine the diagnostic and experimental configuration requirements. As part of a successful Laboratory Directed Research and Development proposal, we have been assisting in the development of a variety of advanced diagnostics to be fielded on Atlas, including linear and nonlinear optical techniques, x-ray diffraction, photoelectron spectroscopy, and flash neutron resonance spectroscopy. All of these techniques are well developed for steady-state measurements, and the development effort lies in adapting them to the dynamic Atlas environment.

Further Information

For further information on all of P-24's projects, refer to the project descriptions in Appendix A. Some of our major achievements are also covered as research highlights in Chapter 2. These include our work in the area of LPI, cylindrical and spherical implosion research at Nova and Omega, MTF research and results, and the continued development of the APPJ.

P-25: Subatomic Physics

Andrea P. T. Palounek, Group Leader
Martin D. Cooper, Deputy Group Leader

Introduction

The Subatomic Physics Group (P-25) is engaged primarily in fundamental nuclear- and particle-physics research. Our objective is to conduct diverse experiments that probe aspects of subatomic reactions, in order to provide a more thorough understanding of the basic building blocks that make up our universe. Although our main focus is basic research, we also have a strong effort in applied programs such as proton radiography. To conduct our research, we often participate in large-scale collaborations that involve physicists from universities and institutions around the world, and we participate in or lead experiments at a variety of facilities. Currently, we are conducting research and developing new programs at Los Alamos National Laboratory and other laboratories, including Brookhaven National Laboratory (Brookhaven) and Fermi National Accelerator Laboratory (Fermilab). The following sections highlight the significant experiments and activities that we are currently pursuing.

The PHENIX Program at RHIC

P-25 has been exploring the subatomic physics that defined the universe at its beginning. Big Bang cosmology pictures a time very early in the evolution of the universe when the density of quarks and gluons was so large that they existed as a plasma, not confined in the hadrons we know today (neutrons, protons, pions, and related particles) (see Figure 1). As operations are commencing at Brookhaven's Relativistic Heavy-Ion Collider (RHIC), the effort has begun to produce a small sample of this primordial quark-gluon plasma in the laboratory and to study its exotic properties. The challenge facing the international collaborators involved in the RHIC program is to identify the fleeting transition into this deconfined phase of matter.

Physics Division has a long tradition of experiments at the high energy-density frontier, and P-25 is playing a major role in defining the search for the quark-gluon plasma and the related physics program for RHIC. To meet these goals, P-25 is playing a key role in constructing two major subsystems for the PHENIX (Pioneering High-Energy Nuclear Interaction eXperiment) detector, one of two major collider detectors at the RHIC facility. The PHENIX

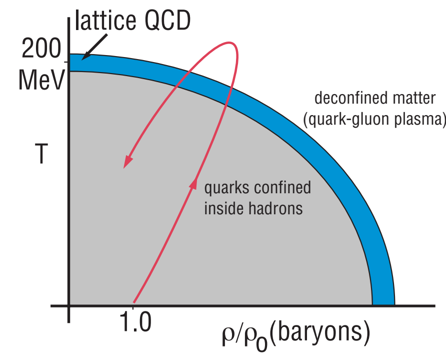


Figure 1. Lattice QCD calculations predict that at higher temperatures and densities, there will be a transition of matter from the confined state to the deconfined state, as shown by the solid band. Research with RHIC will explore this transition of matter.

collaboration currently consists of over 300 physicists and engineers from universities and laboratories in the U.S. and 14 foreign countries. Our work focuses on the multiplicity/vertex detector (MVD) and the muon subsystem. The MVD is the smallest and among the most technically complex of the PHENIX systems. It will surround the region where the two beams of 100-GeV/nucleon ions intersect. The functions of the MVD are to determine the precise location of the interaction vertex and to measure the global distribution and the total number of secondary charged particles; these properties are crucial parameters in fixing the energy density achieved in the collision fireball. A partially instrumented MVD has taken highly preliminary data during the first physics run of the PHENIX.

The muon detectors, the largest subsystem in PHENIX, consist of two sets of position-sensitive tracking chambers surrounding conical magnets at opposite ends of the detector. Muons are identified by recording their penetration into a series of large steel plates interspersed with detection planes, all of which lie behind the magnets. The muon subsystem plays a central role in P-25's physics agenda because it is optimized for examining hard-scattering observables at very high temperatures and densities, where the strong force is smaller and easier to calculate using perturbative quantum chromodynamics (QCD). The first detector, known as the South Arm, is complete and is being moved into the interaction region for data taking in 2001. The North Arm is under construction; its completion date will depend on the availability of funds and periods for installation. (More details on this experiment are available in the research highlight "The PHENIX Detector Program at RHIC" in Chapter 2.)

High-Energy Nuclear Physics

Another area of study in P-25 is parton distribution in nucleons and nuclei, and the nuclear modification of QCD processes such as production of J/ψ particles (made up of a pair of charm/anticharm quarks). We are currently publishing research on this topic from a program centered at Fermilab. This program began in 1987 with measurements of the Drell-Yan process in fixed-target proton-nucleus collisions. Those measurements showed that the antiquark sea of the nucleon is largely unchanged in a heavy nucleus. In our most recent measurements during the NuSea Experiment (E866), we demonstrated a large asymmetry between down and up antiquarks, presumably due to the nucleon's pion cloud (see Figure 3). In addition we showed that the production of heavy vector mesons such as the J/ψ is strongly suppressed in heavy nuclei. We mapped out this effect over a broad range of J/ψ energies and angles. Although the causes of this suppression are not yet fully understood, it is already clear that absorption in the final state plays an important role, as do energy-loss of the partons and shadowing of the gluon distributions. The muon arms at PHENIX are well poised to continue these studies when protons are collided with heavy ions at RHIC.

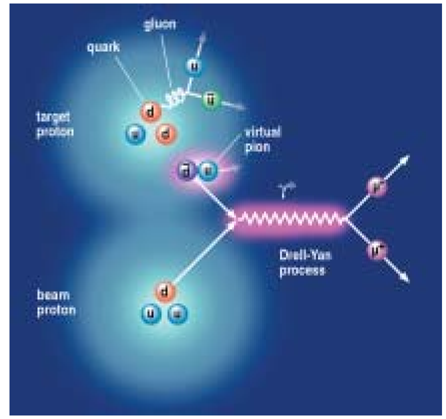


Figure 2. A proton consists of three valence quarks held together by gluons in a sea of quark-antiquark pairs. These pairs may be produced by gluon splitting, a symmetric process generating nearly equal numbers of anti-down, $\bar{d}$, and anti-up, $\bar{u}$, quarks, or from virtual-pion production, an asymmetric process that generates an excess of $\bar{d}$. We can determine $\bar{d}/\bar{u}$ by measuring the properties of the muon pairs produced in the Drell-Yan process, which occurs when a quark in a proton beam strikes a sea antiquark in a target.

Spin Physics at RHIC

The muon detectors at PHENIX are also designed to study which components of the proton carry its spin. When both beams at the RHIC collider are composed of polarized protons, the proton-proton interactions will be directly sensitive to the fraction of spin carried by the gluons (see Figure 2). Previous measurements of deep inelastic scattering have only been sensitive to the sum of the quark and antiquark contributions to the spin, but the availability of polarized protons to induce the Drell-Yan process allows the separation of these two components by measuring the antiquark piece alone. Additionally, by measuring the asymmetry of the charge states of the intermediate vector boson (W), the flavor dependence (*i.e.*, the difference between up and down quark contributions) can be extracted. Spin physics is expected to commence at RHIC after a year or two of heavy-ion experimentation.

Liquid Scintillator Neutrino Detector

P-25 conducts experiments to explore neutrino oscillation, a phenomenon that has great implications in our understanding of the composition of the universe. The Liquid Scintillator Neutrino Detector (LSND) experiment at the Los Alamos Neutron Science Center (LANSCE) has provided evidence for neutrino oscillations, revealing an excess of oscillation events in both the muon-antineutrino to electron-antineutrino ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) and muon-neutrino to electron-neutrino ($\nu_\mu \rightarrow \nu_e$) appearance channels. These two channels are independent of each other and together provide strong evidence for neutrino oscillations in the $\Delta(m^2) > 0.2$ eV^2 region. The LSND results imply that at least one of the neutrino types in each of these appearance channels has a mass greater than 0.4 eV. When combined with estimates of the number of neutrinos present in the universe, the LSND results suggest that neutrinos contribute more than 1% to the mass density of the universe. The existence of neutrino oscillations has great significance for nuclear and particle physics as well because it implies that lepton number is not conserved and that there is mixing among the lepton families; these observations require extensions to the standard models. The LSND experiment, which had its last run in 1998, has also made precision measurements of neutrino-carbon and neutrino-electron scattering, which provide interesting tests of the weak interaction.

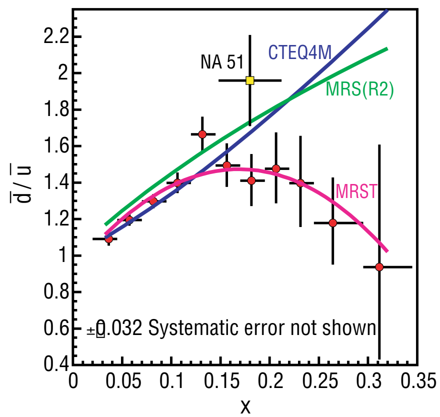


Figure 3. The ratio of $\bar{d}$ to $\bar{u}$ in the proton from the FNAL E866 NuSea as a function of the fraction of the proton's momentum carried by the quark *x*. NA51 was the only previous measurement of this quantity. The curves represent various parameterizations of $\bar{d}/\bar{u}$. The curve that best matches that data, labeled "MRST," was proposed only after the FNAL E866.

Booster Neutrino Experiment

The importance of the LSND results demands a definitive experiment to verify the results, and P-25 has been pursuing the Booster Neutrino Experiment (BooNE) to that end. This experiment will be conducted at Fermilab. The BooNE detector will consist of a 12-m-diameter sphere filled with 770 tons of mineral oil and covered on the inside by 1,280 photomultiplier tubes mostly recycled from the LSND experiment (see Figure 3). The detector will be located 500 m away from the neutrino source, Fermilab's 8-GeV proton booster and new neutrino-production horn. The proton booster will run nearly continuously, and if the LSND results are indeed due to neutrino oscillations, BooNE will observe approximately 1,000 $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation events after one year of operation. Furthermore, assuming oscillations are confirmed, BooNE will make precision measurements of the oscillation parameters and test for charge-conjugation parity violation in the lepton sector. The contractors have given the collaboration beneficial occupancy of the detector tank and electronics rooms at Fermilab. The BooNE detector should be operational by the end of calendar year 2001, and first results are expected two years later.

MEGA

The apparent conservation of muon number remains a central problem of weak interaction physics. Most extensions to the standard models require a much larger mixing than would be predicted by neutrino oscillations. The search for such effects has been a research topic in P-25. Experimental evidence to date shows that muon decays always contain at least one electron and two neutrinos. However, the particle physics community believes in the need to extend the minimal standard model of weak interactions. Searches for decays that violate muon number conservation address these extensions. MEGA was an experimental program designed to make such a search at the Los Alamos Meson Physics Facility (LAMPF, now known as LANSCE). MEGA, which searched for muon decays yielding an electron and a gamma ray (hence, the acronym), completed its data collection in 1995. The extraction of kinematic properties for all of the muon decay events that potentially meet the MEGA criteria is now complete. (Please see the research highlight "New Limit for the Lepton-Family Number Nonconserving Decay $\mu^+ \rightarrow e^+\gamma$ in Chapter 2.) The combined data from the summers of 1993–1995 have not observed any events of the new type without neutrinos. This result improves the current world sensitivity to this process by a factor of 4 to 1.2×10^{-11} (branching ratio with 90% confidence).

Ultracold Neutrons

P-25 is collaborating with the Neutron Science and Technology Group (P-23) in experiments to provide better sources of ultracold neutrons (UCNs), neutrons that can be trapped by ordinary materials. Solid deuterium has been proposed for some time as a material to convert cold neutrons into UCNs. Recently, experiments conducted by Physics Division have demonstrated that coupling a solid deuterium moderator to a high intensity of cold neutrons can produce world-record densities of UCNs (see Figure 4). Using cold neutrons produced in the interaction of 800-MeV protons with tungsten, UCNs have been bottled with a factor of two higher neutron density than reactor-driven sources such as the Institute Laue-Langevin source, the previous record holder. The source of the protons was the LANSCE accelerator at Los Alamos.

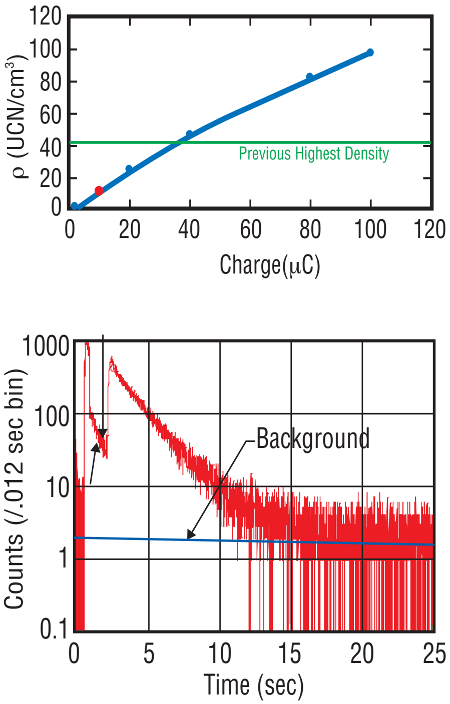


Figure 4. On June 29, 2000, we tested the prototype UCN source with beam intensities similar to those we would use for the full-scale source. The result was the highest density ever achieved of UCNs stored in a bottle, a factor of 2.5 greater than the world's previous highest density. The top plot shows the density achieved as a function of incident proton charge. The bottom plot shows the time structure of the detected UCNs, after the start of the proton pulse at time zero. The UCNs were stored for 1/2 second. About 30,000 UCNs were detected in the run shown, which corresponded to an incident charge of 100 μC of protons and a UCN density of

Electric Dipole Moment of the Neutron

P-25 is also participating with P-23 in a Laboratory project aimed at improving the limit on the electric dipole moment (EDM) of the neutron. Our interest in this topic is driven by the observation of violation of time-reversal invariance in the neutral kaon (K^0) system. Many theories have been developed to explain this time-reversal-invariance violation, but most have been ruled out because they predict a sizable EDM for the neutron, which experiments have yet to verify. Today, new classes of highly popular models, such as supersymmetry, predict EDM values that are potentially within the reach of experiment. In addition, if the observed baryon-antibaryon composition of the universe is due to time-reversal-violating symmetry breaking at the electroweak scale, the range of predicted EDM values is also measurable. We are currently working towards experimentally verifying the feasibility of conducting an experiment that should improve the limit on the neutron EDM by two orders of magnitude to 4×10^{-28} e·cm. A first test experiment has been completed at the Manuel Lujan Center to study the properties of dilute mixtures of helium-3 in superfluid helium-4. Preliminary results from neutron tomography (see Figure 5) indicated that these properties are well suited to the planned experiment.

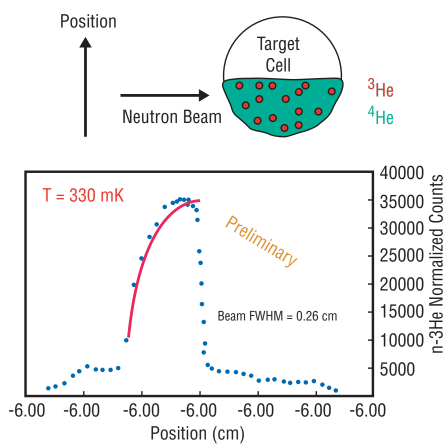


Figure 5. The upper part of the diagram illustrates the idea of neutron tomography. A highly collimated beam of neutrons is incident on a cylindrical cell filled with a small amount of helium-3 in superfluid helium-4. A neutron may absorb on the helium-3, and the reaction products produce light that can be observed and whose intensity is proportional to the amount of helium-3 in the path of the beam. By moving the cell across the beam, experimenters can deduce the distribution of helium-3. The lower part is the results of such a scan when the cell is half full. The sharp edge at the liquid boundary can be interpreted in terms of the size of the beam. The red line represent a purely geometric expectation but neglect many optical effects that will be included in the analysis.

Hypernuclei Physics

One of our recent interests has been the study of lambda (λ)-hypernuclei, where the λ replaces neutrons within nuclei. This substitution explores the strong interaction (the force that holds the nucleus of an atom together). In 1994, we proposed experiment 907 (E907) at Brookhaven's Alternating-Gradient Synchrotron (AGS) to study the reaction: nucleus plus negative kaon transforms into hypernucleus plus neutral pion. This method of production is a novel tool for producing λ-hypernuclei with significantly better energy resolutions than those produced in the previous experiments. Additionally, E907 was capable of measuring the π^0 weak-decay modes of λ-hypernuclei that have never been studied previously. The LANSCE neutral meson spectrometer and associated equipment were moved to the AGS for this experiment. A new data-acquisition system and a new array of active target chambers were successfully installed. We have published the first hypernuclear spectrum using the (K^-,π^0) reaction, and it has a resolution (2 MeV) that is roughly a factor of two better than any previous measurement. In addition, the π^0 energy spectrum that results from the weak-decay of light λ-hypernuclei has also been measured and is under analysis.

Theory

In addition to the fundamental experiments conducted in our group, P-25 has a strong theory component, which consists of a staff member, a postdoctoral fellow, and a number of short- and medium-term visitors from universities and laboratories throughout the world. Theoretical research focuses on basic issues of strong-, electromagnetic-, and weak-interactions topics that complement the present activity of the experimental program and that impact possible future scientific directions in the group. As such, our theoretical team facilitates interaction between experimental and theoretical activities in the nuclear and particle physics community and contributes to a balanced scientific atmosphere within the group. Recent theoretical activity has focused on parity violation in chaotic nuclei, deep inelastic and Drell-Yan reactions on nucleons and nuclei, QCD at finite temperatures, and the EDM of the neutron.

Proton Radiography

P-25 has a very strong applied program in proton radiography (P-RAD). The P-RAD program has three goals. The first is to demonstrate that high-energy proton radiography is a suitable technology for meeting the goals established for the advanced radiography program, the second is to advance the technology, and the third is to apply 800-MeV proton to the needs of science-based stockpile stewardship (SBSS) program. These goals are highly coupled because many of the techniques developed for 800-MeV radiography can be used at higher energies. In the last year alone, we have carried out 28 successful shots that address a wide range of SBSS issues. Additionally, we have moved beyond a successful demonstration of P-RAD at 25-GeV using the AGS at Brookhaven and have begun experiments relevant to the stockpile at this energy. Our successes and experience are being transferred to the designers of the Advanced Hydrotest Facility (see Figure 6). For more information on our P-RAD efforts, refer to the research highlight “Proton Radiography” on this topic in Chapter 2.

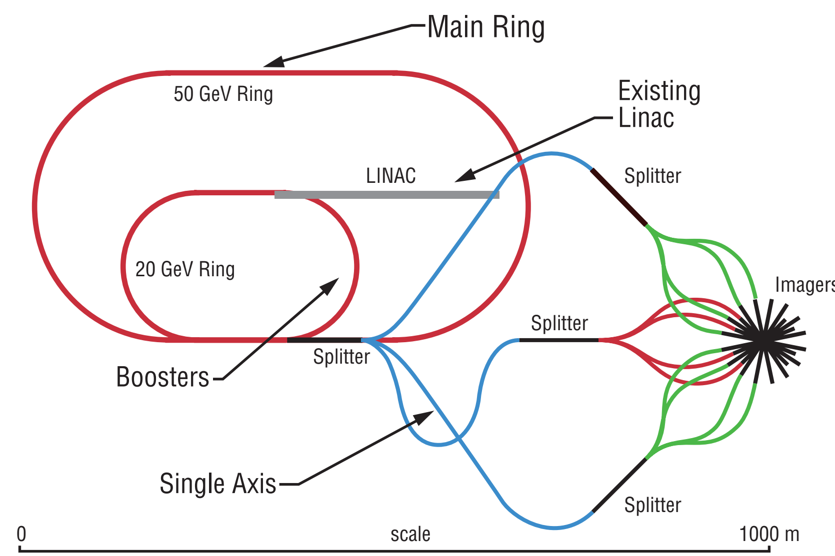


Figure 6. Concept of the P-RAD Advanced Hydrotest Facility (AHF). PRISM, a subset of the AHF, would include the linac injector, the main 50-GeV acceleration ring, a single-axis extracted beam line, a firing point, and a lens system.

Quantum Computation using Cold, Trapped Ions

In another applied program, P-25 is collaborating with P-23 to develop quantum-computation technology. Quantum computation is a new computational paradigm that is much more powerful than classical computation because it allows computing with quantum-mechanical superpositions of many numbers at once. In a quantum computer, binary numbers will be represented by quantum-mechanical states ("qubits"). We are developing a quantum-computational device in which the qubits will be two electronic states of calcium ions that have been cooled with a laser to rest in an ion trap. Once these ions are resting in the trap, we will perform quantum logical operations with a laser beam that is resonant with the qubit transition frequency and is directed at individual ions. We have constructed diode laser systems for the 866-nm and 854-nm calcium ion transitions and a frequency doubler for an amplified 794-nm laser diode. These lasers are locked to an optical transfer cavity to provide continuous, independent tuning with laser stability of 1 MHz. We have designed and built an ultra-stable 729-nm laser capable of resolving motional sidebands of trapped calcium ions, and we have trapped and imaged clouds of ions frozen into strings. Spectra of the 729-nm calcium transition have been studied in preparation for sideband cooling designed to put the ions in their motional ground state.

Education and Outreach

P-25 group members continue to be active in education and outreach activities, both as participants in programs sponsored by the Laboratory and as individual citizens who volunteer their time for various activities. Recent group-member activities include acting as judges for the New Mexico Supercomputing Challenge, participating in career days and college days at New Mexico schools, and visiting classrooms. We also coordinated, organized, and participated in the Teacher's Day at the annual meeting of the American Physical Society's Division of Nuclear Physics.

In addition to these outreach activities, P-25 sponsors several high school, undergraduate, and graduate students to work on projects within the group. Through their individual schools, these students study physics, computing, engineering, and electromechanical technical support, and they supplement their learning through interaction with Laboratory mentors and real on-site experience. Several students are writing theses based on the work they do at P-25.

New Initiatives

Our group is constantly seeking new research opportunities to replace completed ones. At Fermilab, we are members of a collaboration that proposes to extend the range of measurement of the pion cloud feature of nucleons uncovered in with the Drell-Yan process. This effort is in the approval process. We have explored a role for P-25 within the energy upgrade/hall D addition at the Jefferson National Laboratory, and have made suggestions for both experiments and detectors to be used in that facility. Recently, the Japanese Hadron Facility was approved by their government. We have contributed to their ideas for utilizing it by submitting two letters of intent: one for Drell-Yan physics and one for neutrino-proton elastic scattering. Our staff has made a number of visits including two of two months as well as participating in their workshops. We are well poised to be involved if the opportunities continue to look promising. Finally, we have studied the advantages of relativistic electron-nucleus collisions at an eRHIC facility.

Further Information

All of the research described is aimed at increasing our understanding of subatomic reactions, and we are poised to make exciting discoveries in nuclear and particle physics over the next several years. To learn more about these projects, as well as the other work being conducted in our group, please see the project descriptions in Appendix A. Some of our major achievements are also covered as research highlights in Chapter 2. These include our work in high-energy nuclear physics, rare muon decays, and proton radiography.

P-26: Atlas Construction

David W. Scudder,
Group Leader

Introduction

The Atlas Construction Group (P-26) was created in 1999 to consolidate the activities of the Atlas Construction Project. Atlas is a congressional line-item construction project to build a large pulsed-power generator for science-based stockpile stewardship (SBSS) experiments. Construction received first capital funding in fiscal year 1996 and completed performance-acceptance tests in December of 2000. The members of P-26 included electrical, mechanical, and controls engineers; designers; electrical, mechanical, and computer technicians; project-management personnel; operations and administrative-support personnel; and physicists. A number of contract technicians were hired during the assembly of the machine from contractors in Los Alamos and Albuquerque. A number of personnel from other groups and divisions, including the Hydrodynamics and X-Ray Physics Group (P-22), the Plasma Physics Group (P-24) in Physics Division and others from the Dynamic Experimentation (DX) and Engineering Sciences and Applications (ESA) Divisions, played crucial roles on the Atlas team. The P-26 group was dissolved at the end of calendar year 2000 as the pulsed-power machine became ready for experimental operations.

Figure 1. The Atlas pulsed-power machine.

Atlas Mission

The mission of the Atlas construction project was to contribute to continued confidence in the nuclear stockpile by providing an experimental tool capable of measuring fundamental processes important in the function of nuclear weapons, while also contributing to the basic science of the behavior of materials at high-energy density. The machine built to fulfill this mission generates pulses of high-voltage electrical power with currents up to about 30 MA and pulse lengths several μs long.

The underground detonation and testing of nuclear weapons was suspended by the United States in 1992. Up until that time, confidence in the nuclear-weapon stockpile was assured by exploding weapons and directly measuring yield and other performance characteristics. When political considerations made such tests impossible, the nature of certification of the stockpile changed fundamentally. Without the possibility of nuclear tests, confidence into the indefinite future can only be achieved by developing a rigorous understanding of the physical phenomena that occur in nuclear weapons, then incorporating models of those phenomena into integrated computer simulations. These computer simulations, which require the most powerful computers on the planet, are then used to try to test the behavior of weapons while taking into account effects of aging of materials, changes observed in stockpile devices, necessary changes in manufacturing techniques, and other factors that could possibly affect the device's performance. This process is made much more difficult by the fact that the physical models were, at best, in rudimentary form before testing was stopped. So, little experimental data directly testing those models from underground tests is available to guide present development.

SSSB requires a heavy reliance on computer calculations to explore regions of parameter space unavailable in the laboratory. The possibility of significant errors due to inadequacy of physical models in the computer programs is a serious concern. Indeed, the basic principal of the scientific method is that predictions must be tested by experiment. Thus the importance of providing experimental tools to test the computational models under conditions as near to those where they are being applied in computers simulations cannot be overemphasized.

Several different types of tools are required. Many conventional laboratory tools, such as Hopkinson bar, diamond-anvil devices, and gas guns can be used to provide important data, although usually under conditions far removed from those in weapons. High-power lasers can approach the extremely high energy density present in weapons, but in extremely small volumes and times. Pulsed-power-driven x-ray sources, such as the Z pulsed-power machine at Sandia National Laboratories, can approach the energy densities of high power lasers. Atlas is designed to provide larger experimental volumes (much larger than the grain size, for instance) for longer times in a configuration useful for isolating and exploring hydrodynamic effects.

Atlas Design and Operation

Atlas is a state-of-the-art pulsed-power facility that will allow scientists to explore material behavior at extreme temperatures and pressures, providing data of interest to materials science and stockpile stewardship. Atlas works by storing a large amount of electrical energy, up to 23.5 MJ, in capacitors at high voltage. These are connected through fast switches in a low-inductance configuration to a metallic cylinder, usually made from aluminum. Typical dimensions of the cylinder are 8.5 cm in diameter, 2-mm thick and 4-cm long. When the current pulse (as high as 30 MA) flows axially along the cylinder, with 99%

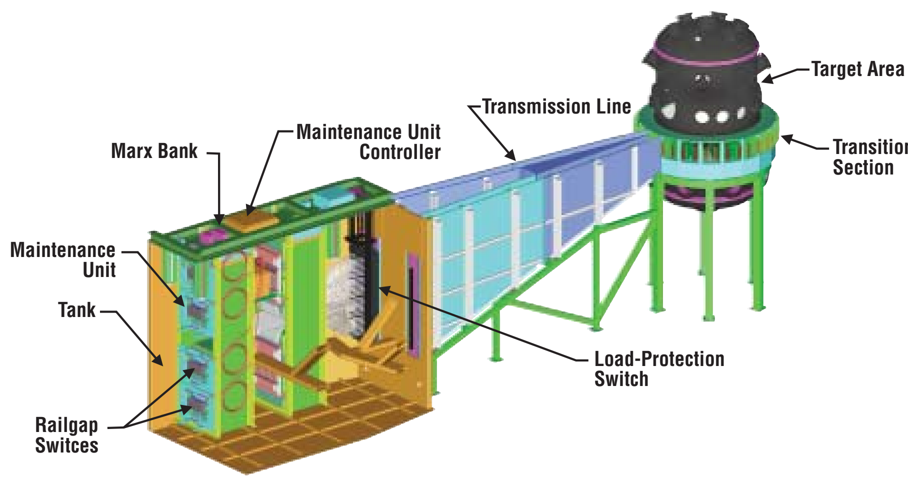


Figure 2. Components of the Atlas machine (see text for details).

drive symmetry, it produces a large magnetic field. The magnetic field, in turn, exerts a force on the cylinder that tends to compress it radially. This causes the cylinder to deform plastically and implode toward the axis. While moving a few centimeters, this liner can reach velocities exceeding 10 mm/µs (equal to 10 km/sec or 22,000 mph). This is about equal to the escape velocity from earth. Some experiments study the behavior of this liner directly, while others use it to impact a target designed to illustrate some particular physical effect. Several planned experiments are described later.

Atlas uses 384 large capacitors, each of which stores about 60 kJ at 60 kV. Modules consisting of four capacitors are grouped in an arrangement called a Marx bank (the full machine contains 96 Marx banks). In a Marx bank, the capacitors are charged in parallel but discharged in series, such that their voltages add. Thus the machine produces 240 kV at maximum charge. Groups of four Marx banks are built into a structure called a maintenance unit, which can be easily removed for maintenance or repair. The whole machine consists of 24 maintenance units. Maintenance units are mounted in tanks filled with oil, which provides high-voltage insulation. The machine consists of 12 tanks arranged in a circle about 100 ft in diameter.

Current from the capacitor modules is carried to the target region at the center of the machine by transmission lines. Each maintenance unit has a transmission line made from three aluminum plates mounted vertically and immersed in oil. Each transmission line has its own load-protection switch, which prevents current from flowing to the target area in the event of prefire. These load-protection switches protect the delicate and often expensive experiments and diagnostics in the target area from damage due to a prefire. The transmission lines are designed to deliver the current to the target area with very low inductance. This allows the current to rise very quickly—up to 30 MA in only 4.5 µs.

A computer control system monitors the voltage of each maintenance unit (see Figure 3). Atlas is one of the first pulsed-power facilities to implement completely distributed computer controls, a challenge in such high-electromagnetic (EM) environments. These control systems continuously monitor all critical aspects of machine performance and can detect and respond to problems in only tenths of a second. EM shielding protects critical components,

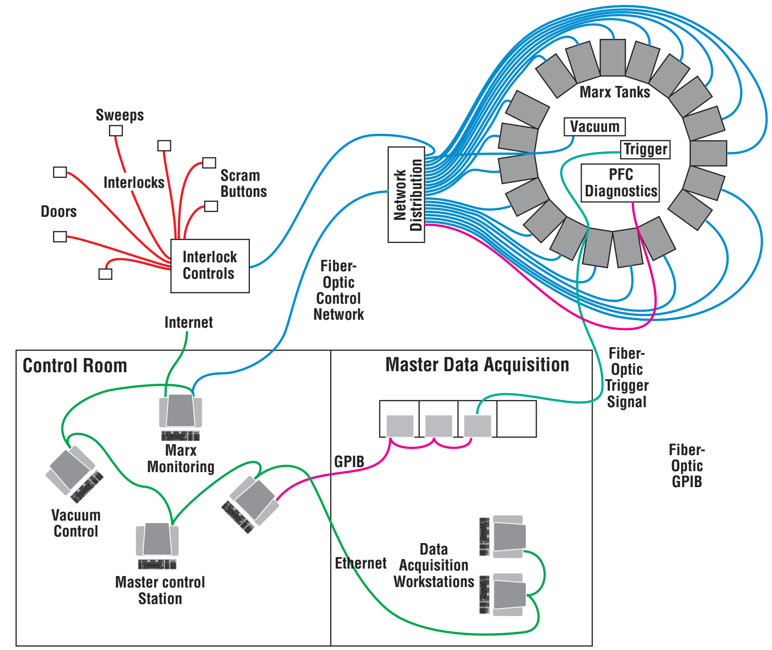


Figure 3. A schematic of Atlas's distributed computer control network (see text for details).

and all high-speed communication occurs over fiber-optic cables, which are unaffected by the high-EM environment. Several layers of built-in redundancy and fail-safe systems ensure that the machine will safely shut down in the event of any problems.

In the center of the machine, the transmission lines all connect to a six-foot diameter hub that directs the current to the cylindrical liner. The transition section transfers current from the transmission lines to the power-flow channel, which delivers the current to the target (see Figure 4). The transition section was the most challenging component to design and fabricate because of the enormous forces and electrical stresses the current puts on the metal surfaces and insulators as it concentrates into this section. The power-flow channel was also challenging because the magnetic pressures on the conductors of the center region exceed the yield strength of any metal.

The transition section serves as the "hub" of the machine, providing structural support for the power-flow channel and target chamber and absorbing much of the shock delivered by the current impulse. Our design cleanly translates the current from the vertical transmission lines to the disk/conical power-flow channel, which delivers the current to the target. Our design maintains mechanical and electrical integrity during the shot despite the destruction of a significant portion of the channel, and it uses relatively low-cost hardware that can easily and quickly be replaced after each shot. Our power-flow channel design also allows for many clear lines of sight to the target for diagnostic tools. Windows in the target chamber even allow some diagnostics to be set up outside the target area.

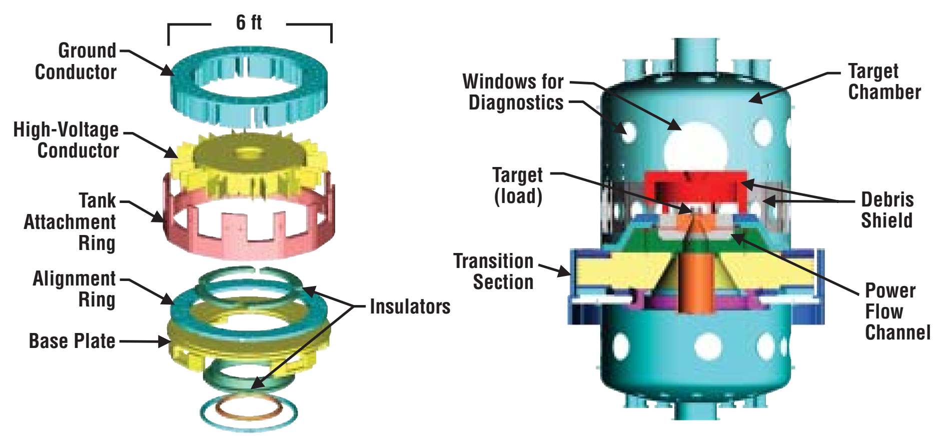


Figure 4. Atlas transition section and target area.

Atlas Construction

Two components of the Atlas machine presented significant challenges: the capacitors and the main switches, known as railgaps (see Figure 5). During the early years of the project, testing was performed on both of these components. Prototype capacitors were purchased and tested until end of life to select a vendor who could provide units that would survive for the design life of the machine, 10 years. Railgaps were tested extensively to determine their pre-fire rate and maintenance cycles. In all, about 40,000 shots were taken on a test stand.

Design for the Atlas machine was completed in mid-1998. Approval to proceed with construction was obtained from the Department of Energy at that time. A number of modifications had to be made to the building which houses Atlas, such as reinforcing the floor to hold the weight of the oil-filled tanks. The first maintenance unit was built and tested to verify that the design would work. Fabrication of the rest of the hardware and assembly of the Marx banks was initiated during 1999.

During 2000 a number of contractors were brought onto the project to assist with the assembly of the machine. The first tanks arrived at the end of January 2000. By September Atlas was structurally complete. High-voltage testing of the machine was successfully completed in December 2000, with a demonstration shot at 28.6 MA.

Figure 5. “Railgaps” are pressurized-gas switches that connect the capacitors in series when they are triggered. These railgap switches keep the current from flowing through the system until all maintenance units have reached full voltage.

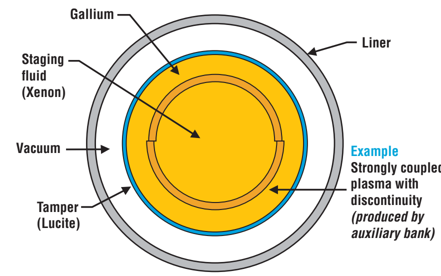
Atlas Experiments

Among the first experiments anticipated for Atlas are hydrodynamic features, friction, and spall. Following are brief descriptions of each.

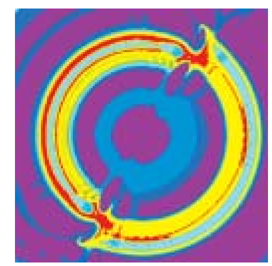
Hydrodynamic Features

The ASCI Program (Accelerated Strategic Computing Initiative) requires computer programs to accurately model hydrodynamics in three dimensions. In order to rely on these computer calculations, we must have experimental data against which to test them. The results of some Pegasus II experiments (one shown in Figure 6) have provided confirmation to modeling predictions. Other Pegasus II experiments showed that some of the codes could not match experimental results. This stimulated improvements in the hydrodynamics models used in the codes.

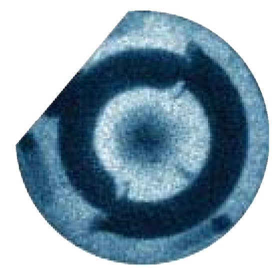
Atlas will allow experiments in completely new regimes, much closer to those experienced in weapons detonation. Atlas provides an excellent test bed for



(a) Experimental schematic



(b) RAGE calculation



(c) Pegasus II data

Figure 6. (a) The schematic shows the experimental setup for a hydrodynamic experiment. The gallium layer is 2 mm thick, but one half has a smaller radius than the other so that a step is formed at the junction of the two halves. (b) Mathematical models predict that vorticity and mixing of materials will occur as the main shock passes across this uniform boundary. (c) Experiments on Pegasus II have confirmed this predicted result.

comparing ASCI calculations of strong shocks propagating in converging geometries. In the first hydrodynamic features experiments on Atlas, an aluminum liner will be imploded onto a metal cylinder of tin that has an off-axis cylindrical hole filled with butane. The impact of the liner will generate an initially uniform converging shock in the tin. As the shock crosses the boundary with the butane, its velocity will change, which will result in a change in its center of convergence.

Diagnosis of the shocks' behavior will be performed using radiography and laser backlighting. X-ray heads vaguely similar to those in a dentist's office will be mounted beside and below the target. These heads produce a short pulse, about 10 ns long, which can resolve the action of the liner and the shock waves. X-ray pictures will be taken during the liner implosion, to measure its velocity, and during the shock propagation. A short-pulse laser will be shown along the axis of the butane to observe the location and shape of the shock wave at one instant of time.

The results of this experiment will be compared with ASCI calculations to test the computer codes' accuracy. Similar experiments on a smaller pulsed-power generator, Pegasus II, forced improvements in two ASCI codes.

Friction

When a shock wave propagates parallel to or oblique to an interface between materials of different density, it will try to move at different velocities in the two materials. Friction at the interface will tend to drag one material ahead and hold the other back. Atlas provides an opportunity to study this phenomenon in conditions similar to those in a weapon.

In one version of this experiment, the liner is imploded onto a central target made of a stack of disks of materials with different densities (Figure 7 shows radiographs of a precursor Pegasus II experiment). Radiography cannot penetrate the denser material but can see through the lighter one. Small pins made from dense material are imbedded in the light material near the interface. When the imploding liner drives a shock along the interface, the pins show any deformation of the light material near the interface because of frictional drag. The shapes and positions of the pins are recorded with x-radiographs.

Spall

A strong shock wave that propagates through a material is followed by a release wave as the material behind the shock slows. The pressure in the material in the release wave can go negative, putting the material in tension. If the release wave is strong enough, the negative pressure can cause the material to fracture, generating cracks and voids. Atlas can be used to produce spall in targets, which can be studied with axial radiography. In some cases, the targets may be recovered for material analysis.

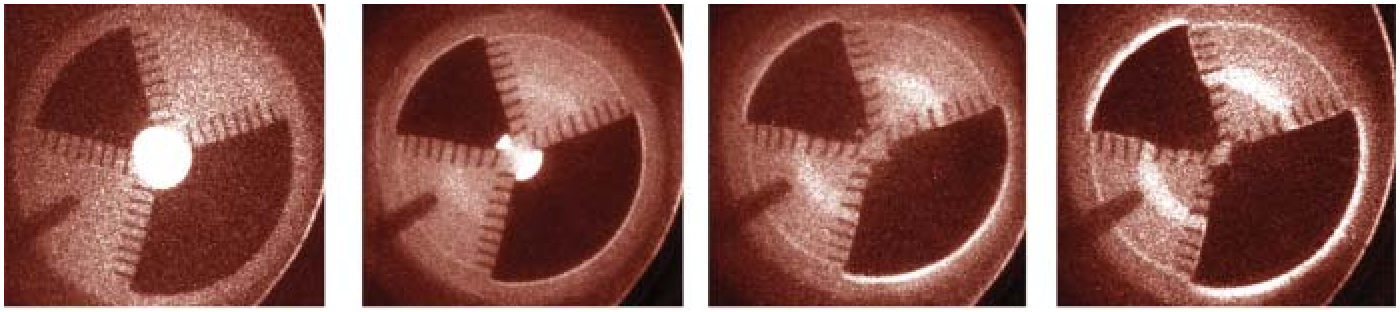


Figure 7. This Pegasus II experiment studied interfaces between tungsten and aluminum. The tungsten is so dense that we can see no x-rays penetrating it in this axial radiograph. However, deformation of the aluminum near its interface with the tungsten can be measured using small tracer pins, visible in the image, mounted perpendicular to the interface. Atlas will provide the opportunity for experimentation with larger targets and longer-duration shock waves than were possible with the Pegasus II apparatus.